Benefits of Open Eye Methodology

Open Eye MSA White Paper

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2 Introduction

Today's hyperscale datacenters contain up to one million servers plus storage. These need to be interconnected with high speed links to transfer data quickly and efficiently between processor and storage memory. The datacenter architecture varies depending on the application (search, online retail, AI, supercomputing, etc.), but the link requirements are very similar – all applications need high bandwidth, low cost and low power interconnects. Keeping power consumption low is critical to minimize operational costs as these not only include the cost of the power for the module but also the cost to cool the module. Applications such as AI and high performance computing (HPC) also require low latency links to maximize compute efficiency.

In the 5G Wireless front haul market, new emerging applications such as virtual reality, augmented reality, mixed reality, industrial process automation, remote control of vehicles and autonomous driving require low power, low cost and low latency links. Due to the large deployment volumes required to provide network coverage and high bandwidth per user, the need for low cost, low power and low latency is critical. The bandwidth increase in the front haul application also drives subsequent increased bandwidth in the backhaul application. The backhaul market also requires low power and low cost.

At 50 Gb/s, the industry has moved to PAM4 to increase link capacity whilst not increasing the bandwidth requirement significantly compared to 25 Gb/s NRZ links. During development of 50 Gb/s PAM4 standards, some new test concepts were developed that have had some unintended consequences. One concept that was developed is Transmitter Dispersion and Eye Closure Quaternary (TDECQ). TDECQ uses equalization at the receiver to compensate the transmitter before assessing the transmitter performance. The consequence of this approach is that the real receiver is also expected to have at least this level of equalization capability. This generally favors a DSP-centric approach which increases latency and also limits technology choices. This type of equalization also costs in terms of increased power dissipation and increased complexity as such approaches require implementation of robust optimization algorithms for equalizer tuning.

The Open Eye MSA is an industry group formed to define a set of optical module PMD specifications that provide optimum port bandwidth, low power and low latency and density for next generation optical modules. The specifications developed by the MSA leverage and extend the industry's existing test methodology for measurement of eye diagrams and BER. Modules that comply with the Eye Opening specifications will interoperate across multiple vendors and are compatible with IEEE link budgets enabling reuse of the existing fiber infrastructure.

This MSA work was initiated in response to large data center and 5G wireless network requirements for higher speed, higher density and lower latency optical module solutions. The existing optical specifications assume the likelihood of closed eye transmitters and the subsequent need for a complicated power-hungry receiver resulting in complex test methods. The Open Eye MSA members believe this is not the best solution for 50 Gb/s PAM-4 systems.

3 TDECQ

The IEEE 802.3 standards for PAM4 PMDs have used TDECQ and other metrics to ensure the transmitter performance is adequate. TDECQ is a measure of Vertical Eye Closure (VEC) and is calculated by assessing the inner eye openings and the level of noise impairment that can be added to signal to increase the bit error rate (BER) to 2.4×10^{-4} (KP4 FEC threshold). The more noise that can be added, the better the eye opening is and the lower the TDECQ value is. TDECQ is therefore a measure of the impact of the transmitter on the receiver sensitivity only.

To protect the receiver, other measures have been used such as constraining the FFE tap weights and the value of C_{eq}. These techniques constrain the equalization that can be applied to the transmitter eye shape at the reference receiver. PAM-4 systems are linear (meaning that equalization at the receiver can be equally made at the transmitter within certain limits and conditions) so these constraints can be worked around to some extent by applying transmitter pre-equalization. Such additional constraints that are applied to the equalization through TDECQ are reflected in receiver sensitivity only. The current IEEE standards for 50 Gb/s PAM-4 PMDs do not have any protection for the receiver against overshoot and undershoot and eye center position within a 1 UI period.

Another aspect of TDECQ is that the FFE equalization methodology is undefined. This aspect of TDECQ can result in a wide range transmitter performance for the same TDECQ value. The TDECQ limit line shown in Figure 1 is a line of constant TDECQ and indicates different transmitter characteristics that are possible for the same value of TDECQ. Some of these different transmitter characteristics are equalizable and others are not. (The vertical axis in Figure 1 is the penalty associated with impairments that are not equalizable such as noise and ISI that is outside the TDECQ equalizer range. The horizontal axis is the penalty associated with noise amplification caused by the equalizer as it equalizes the transmitter bandwidth.)

The transmitter manufacturing data shown in Figure 1 clearly shows that 50 Gb/s transmitters are pre-equalized to lie close to the vertical axis indicating that $C_{eq} = 1$ (or 0 dB). The implication of this is that the receiver equalization is not able to improve the signal further. (Note that C_{eq} is actually the noise enhancement factor of the equalizer. A C_{eq} of 1 indicates that there is no noise enhancement and no noise reduction caused by the equalizer. Whilst a value for C_{eq} of 1 does not guarantee that the equalization is flat, in general this appears to be reasonably true for a wide range of transmitters.)

Figure 1 clearly shows that an optimized transmitter does not require equalization at the receiver as presupposed by the TDECQ measurement.

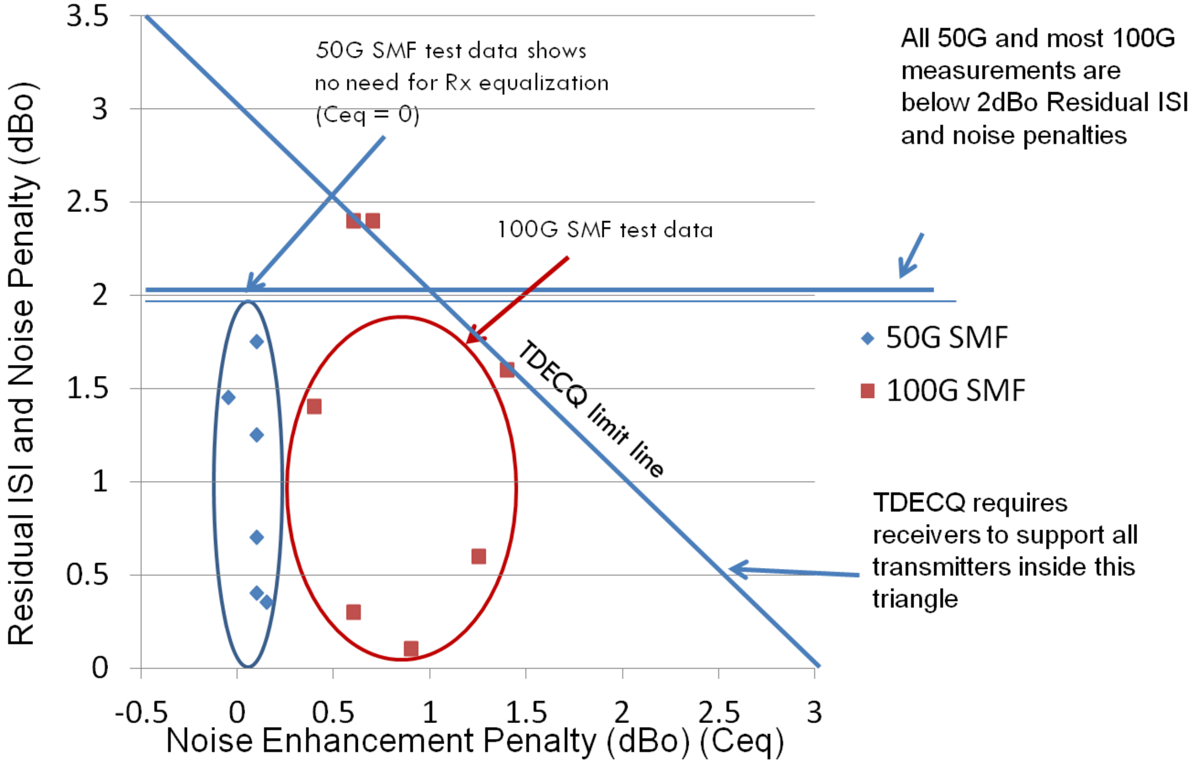


Figure 1 Graph of TDECQ plane showing measured 50 Gb/s and measured 100 Gb/s transmitter performance

3.1 Limitations of TDECQ

A good transmitter requires optimization for good receiver sensitivity, good mid-band BER performance and good overload performance. As mentioned previously, TDECQ is a measure of vertical eye closure and its impact on receiver sensitivity only. For 50 Gb/s PMDs, the IEEE standard does not included protection for the receiver at overload and in the mid-band BER floor. (The IEEE standards at 100 Gb/s have recognized this problem and are starting to address overshoot.)

Overshoot is a key parameter that affects receiver overload performance. The overshoots (and undershoots) give the input signal a much wider dynamic range than the OMA_{outer} of the signal indicates. The linearity of the receiver can be become stressed with the overshoots and undershoots giving rise to distortion of the signal. As distortion is non-linear, it can be difficult to equalize and compensate.

In the mid-band BER floor region, distortion can also interact with other component characteristics to produce unexpected performance. The distortion can be generated at any point in the analog portion of the link (i.e. driver, modulator, photodiode, TIA, etc.).

4 Open Eye System Methodology

The Open Eye approach is based on distributing overall link equalization in a balanced manner between transmitters and receivers allowing for implementation using a wide variety of technologies including lower power, low latency, analog technologies. The Open Eye approach does not preclude DSP equalization technology if this is preferred for some applications.

By balancing equalization between optical module transmitters and receivers such that transmitters are required to equalize for any of their possible shortcomings and likewise receivers must equalizer for any of their limitations, the impact of the Open Eye transmitter performance correlates closely to the sensitivity impairment caused with an Open Eye receiver. This is not always strictly possible with IEEE TDECQ based systems where the impact of the real receiver's equalizer on the transmitter can be difficult to determine.

The normative requirements of an Open Eye compliant transmitter include both a deterministic PAM-4 Eye Mask and a statistical vertical eye closure metric (i.e. VEC_{stat}), both measured at the optical module's TP2 test point. An Open Eye receiver must pass a stressed receiver sensitivity test at TP3 based on an input PAM-4 signal degraded from that of a compliant transmitter.

5 Eye opening measurements

5.1 What causes eye closure

Optical transmitters based on PAM-4 modulation exhibit an inherent eye closure in both power and time which NRZ transmitters are not subject to. For link budgeting purposes a PAM-4 optical transmitter automatically incurs a 4.77dB optical power penalty vis-à-vis an NRZ transmitter but importantly the eye widths of the PAM-4 signal's sub-eyes also drop by approximately 0.25UI for typical transmitters due to the finite rise/fall times of transmitters as PAM-4 signals transition between their intermediate levels.

An important concern in PAM-4 systems is the fidelity of amplification from key components such as laser drivers, EMLs and TIAs, which are typically intended to be as linear as feasible in order to create minimal additional eye distortions and non-idealities. This type of eye closure due to the nonlinearity of gain blocks was less of a concern for NRZ systems (due to NRZ having a two level signal) but is of paramount importance within PAM-4 systems (with four amplitude levels that need to be maintained with equal spacing). The degree to which eye linearity can be maintained has a direct consequence on how much eye closure will be generated within the system and ultimately at the optical receiver slicer/sampler. Linearity not only refers to amplifier gain compression, which can for instance skew PAM-4 eye levels and compress either upper and/or lower eyes, but also to amplifier THD (Total Harmonic Distortion) and group delay variation (GDV) which can have more serious consequences for PAM-4 signals as they traverse the various system gain blocks. Also, especially within PAM-4 systems, serious eye closure effects can take place at transmitters when laser variability over temperature is not properly managed or correctly accounted for. Laser bandwidth and LI curve characteristics can vary significantly, especially at higher temperatures, and the interplay of driver and various laser behaviors can create excessive eye closures at the transmitter TP2 test point.

Many of the intrinsic sources of eye closure within PAM-4 IM/DD optical systems are identical to those encountered with traditional NRZ IM/DD architectures however if not properly budgeted or managed, can lead to lower than expected performance margins and system robustness. Several sources of eye closure which are usually of paramount concern include timing jitter (both deterministic and random), laser RIN, modulator linearity, optical transmitter modulation bandwidth, optical crosstalk, fiber chromatic dispersion (for single-mode systems), photodiode linearity, TIA noise, TIA bandwidth, TIA GDV (Group Delay Variation) and TIA linearity.

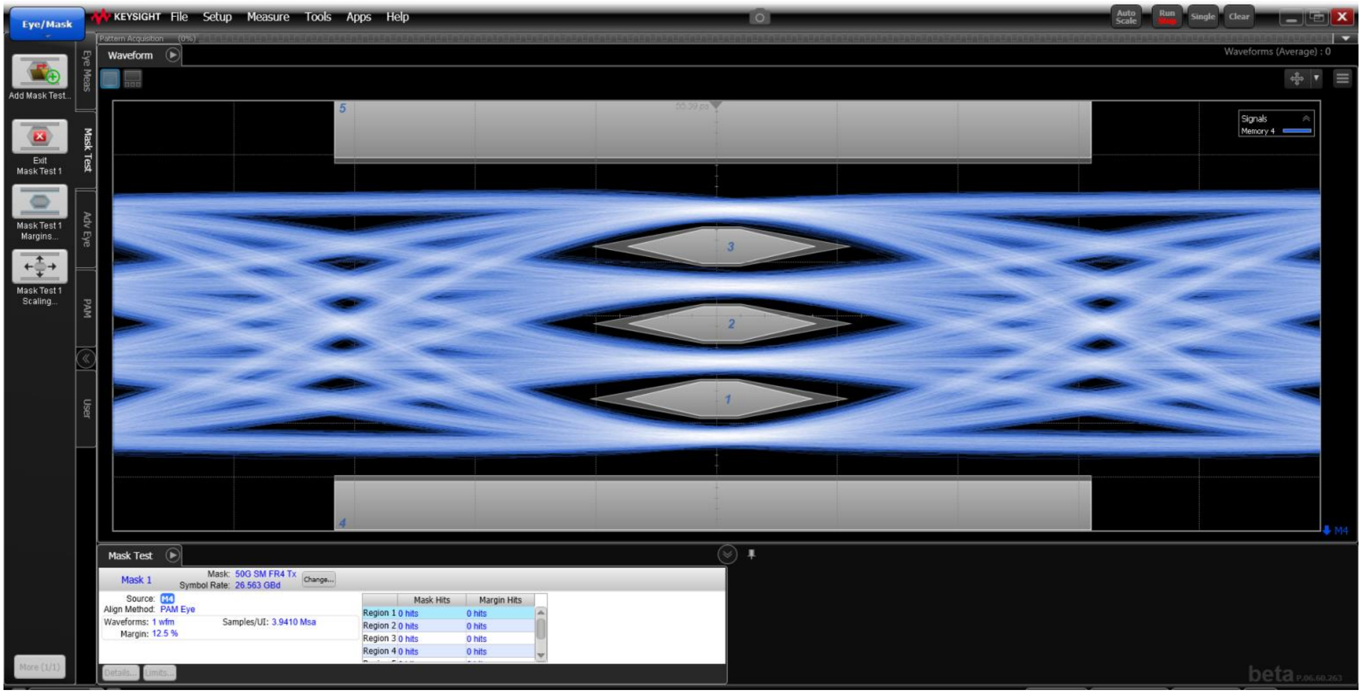
In general, the consequence of optical transmitters with insufficient modulation bandwidth can lead to architectures which require excessive amounts of transmitter pre-distortion and more complex architectures where power-hungry DSP based receivers with more sophisticated equalization are required to manage challenging optical links. Large amounts of equalization can also cause unexpected system behavior and inter-operability problems. Equalization also generally costs in terms of power (extra gain required to overcome equalization losses), complexity (to control the equalization requirements over temperature and life) and in how components are tested and ultimately cost (die size).

It would be easy to infer from the discussion above that we are doomed by the many problems that can happen. There are various techniques that can overcome these problems. We believe the Open Eye approach overcomes this in an optimal way.

5.2 Open Eye Transmitter Measurements

Eye opening measurements based on meeting minimum transmitter eye masks have been the foundation for guaranteeing a minimum set of performance metrics for 10G, 40G and 100G NRZ client optical modules. This MSA adapts that well-defined and accepted approach to capture the specific properties of PAM-4 signals and performance of optical transmitters using a prescribed PAM-4 transmitter mask. IEEE PAM4 standards have not employed the eye mask due to the assumption that the transmit eye may be closed, as discussed earlier.

The Open Eye PAM4 mask builds upon the concept of minimum PAM4 eye openings as defined in OIF CEI-56G-VSR chip-to-module electrical specification which defines a minimum eye height and eye width for each of the PAM4 sub-eyes along with a ‘Horizontal Eye Width’ mask ensuring that there is acceptable skew between the sub-eyes.



Mask 1
Mask: 50G SM FR4 Tx
Symbol Rate: 26.563 GBd
Source: M4
Align Method: PAM Eye
Waveforms: 1 wfm
Samples/UI: 3.9410 Msa
Margin: 12.5 %

	Mask Hits	Margin Hits
Region 1	0 hits	0 hits
Region 2	0 hits	0 hits
Region 3	0 hits	0 hits
Region 4	0 hits	0 hits

Figure 2 *Eye Mask defining allowable eye openings and over/undershoots*

An example of an Open Eye PAM-4 transmit mask, with forbidden regions highlighted in gray, is shown in Figure 2. The minimum required mask dimension is in light gray, with the dark gray representing mask margin. This transmitter mask, which is used as the basis for the Open Eye deterministic specification, requires each sub-eye have a minimum eye height and width and that the signal not incur into the hexagon. Also, the upper and lower eyes are allowed to 'float' with respect to the middle eye implying that certain amounts of skew and nonlinearity due to level mismatch are permissible. The Open Eye mask has some unique features compared to legacy optical eye masks. Since the mask is intended to limit deterministic eye closure, the test is performed with waveform averaging to remove random noise and jitter. Unlike the legacy 'hit-ratio' method which allows a small percentage of waveform samples to violate the mask, the Open Eye mask does not allow any hits. Instead, the Open Eye mask captures a complete waveform and overlays all symbols to ensure that ISI is controlled.

Overshoots and undershoots of the PAM-4 signal are also allowed but again not beyond prescribed limits as represented by the upper and lower gray bands in the figure. None of these requirements are constrained by the TDECQ approach for 50 Gb/s. Recently, the IEEE has recognized the need to limit overshoot and undershoot in newer 100Gb/s PMDs and recently implemented direct measurements on the TX waveform to screen out excessive transients.

5.3 How to measure Open Eye transmitters

Device specifications and the test procedures that support them are intended to ensure that when the transmitter, channel, and receiver are connected, a working link will result. Test procedures specified in IEEE documents for PAM-4 based optical transmitters have enabled the needed interoperability across multiple module vendors. However, the majority of the burden of system equalization is placed on the module receiver in order to accommodate the widest variety of transmitter performance. This has also resulted in a complex test methodology where a transmitter is observed with an ideal virtual equalizing receiver that must be optimized for lowest system level power penalty. If transmitter performance can be restricted to higher quality ‘open eyes’, both the receiver architecture and transmitter test methods can be significantly simplified. The Open Eye test methods deviate from the IEEE methods for these reasons.

There are a variety of specifications for the Open Eye transceiver that are well known through use in IEEE standards such as OMA, extinction ratio, and linearity. These are included in the Open Eye specification. Two measurements are used as the primary indicators of transmitter signal quality: the deterministic eye mask and a VEC statistical parameter (i.e. VEC_{stat}). These measurements differ significantly from IEEE methods and will be discussed in detail. Transmitter dispersion and eye closure quaternary (TDECQ) is a test method originally developed within the IEEE 802.3bs project to assess the effective power penalty of a transmitter due to inherent eye closure and channel dispersion. It is used to account for how much of the link budget is consumed due to transmitter eye closure. Noting the use of a DSP-based receiver as mentioned above, the eye closure is observed using an oscilloscope after passing the signal through an ideal virtual 5-tap feed-forward equalizer. The use of the ideal virtual equalizer complicates the test method. Added test time is required to optimize the equalizer and variation in optimization schemes can lead to variation in test results. Open Eye also requires a measurement to account for transmitter eye closure, but since there is no assumption of receiver equalization, the test method is significantly simplified compared to IEEE TDECQ.

Vertical eye closure statistical (VEC_{stat}) is essentially a simplified version of IEEE TDECQ. The result provides a power penalty value that indicates the increased power required from a transmitter, or increased sensitivity required at the receiver to compensate for transmitter eye closure. Similar to other transmitter power penalty metrics, this additional power is assessed relative to an ideal transmitter with no eye closure. An oscilloscope captures the transmitter waveform and performs a symbol error ratio (SER) analysis of the signal. Virtual noise is added to the signal until the target SER is observed. The better the eye opening, the more noise that can be added. A virtual ideal waveform (no eye closure) with the same optical modulation amplitude of the test signal is created, and virtual noise is added to this signal until the target SER is observed. Typically, more noise can be added to the ideal signal than the test signal. The ratio of the two added noise values represents the transmitter eye closure penalty. The better the eye opening, the smaller the penalty.

In addition to not requiring a virtual equalizing receiver, VEC_{stat} also modifies the behavior of the receiver decision circuit compared to IEEE TDECQ. There are several parameters that define the receiver behavior and are emulated in the TDECQ/VEC_{stat} analysis.

- Ability to optimize the sampling time within the symbol period. IEEE allows the ideal virtual receiver to position the ideal sampling position anywhere within the symbol interval, whilst Open Eye is more restrictive, with the measurement restricted to the middle of the symbol interval (seen below as the 'Histogram Adjustment Limit')
- Ability to adjust the sampling amplitude threshold relative to an ideal linear PAM4 spacing. IEEE and Open Eye both allow the sampling threshold to deviate slightly from ideal linear positions (seen below as the "Threshold Optimization")
- Allowance for uncertainty in the ideal sampling time. IEEE TDECQ is observed with two histogram slices located 0.1 UI apart. This assumes that the receiver may make decisions up to +/- 0.05 UI away from an ideal sampling time. Open Eye assumes half that uncertainty at +/- 0.025 UI, with the histograms placed 0.05 UI apart (seen below as the 'Histogram Spacing')

Preset: IEEE 802.3cd Final

Use the settings in this tab to globally configure all TDECQ Measurements and Equalizers.

Target SER: 4.80E-4

Histogram Properties

Histogram Width: 0.04 UI

☑ Optimize Histogram Times

Histogram Spacing: 0.10 UI

Adjustment Limit: 1.00 UI

Threshold Optimization

☑ Enable

Adjustment Limit: 1.0 %

Threshold optimization is able to move the thresholds from the standard definition by at most the percent of Outer OMA specified by *Adjustment Limit*.

Preset: Open Eye - VEC Statistical 2.0

Use the settings in this tab to globally configure all TDECQ Measurements and Equalizers.

Target SER: 4.80E-4

Histogram Properties

Histogram Width: 0.02 UI

☑ Optimize Histogram Times

Histogram Spacing: 0.05 UI

Adjustment Limit: 0.05 UI

Threshold Optimization

☑ Enable

Adjustment Limit: 1.0 %

Threshold optimization is able to move the thresholds from the standard definition by at most the percent of Outer OMA specified by *Adjustment Limit*.

Figure 3 Configurations for TDECQ (left) and VEC$_{stat}$ (right)

The differences between the IEEE and Open Eye configuration are based on expected receiver differences and extensive module level verification. Specifically, the histogram spacing was adjusted to obtain one to one agreement between the change in VEC$_{stat}$ and the change in receiver sensitivity (as shown in Figure 4), indicating that VEC$_{stat}$ is a valid predictor of system level power penalty.

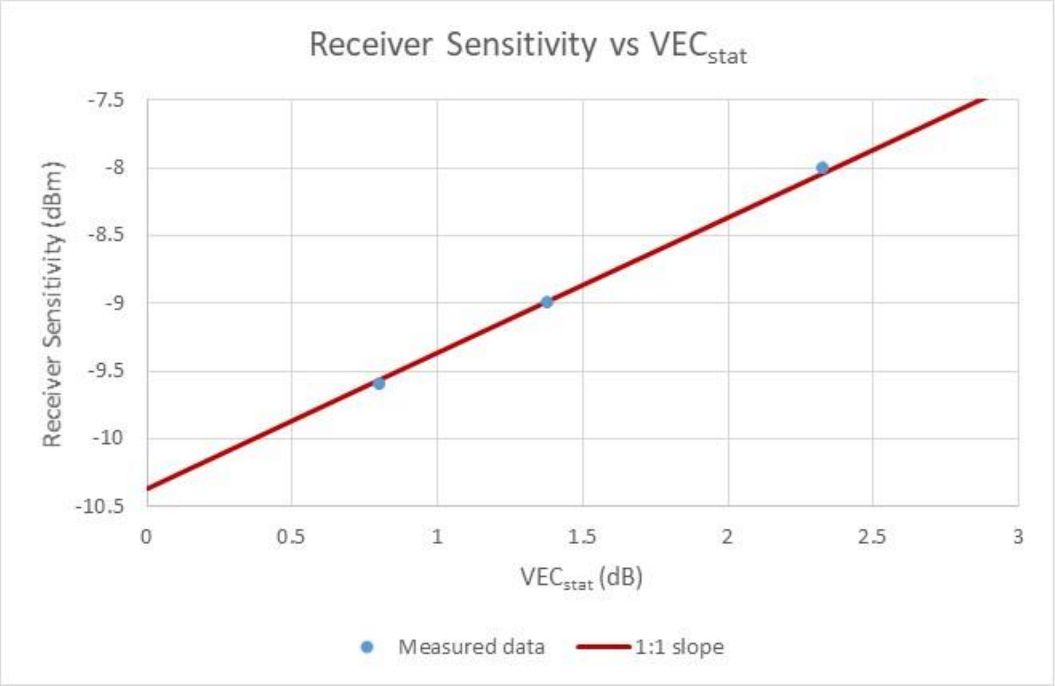


Figure 4 Plot of measured receiver sensitivity versus VEC$_{stat}$ showing good 1:1 correlation

The eye-mask has been a primary quality metric for NRZ transmitters for decades. When PAM-4 schemes were developed in IEEE, the eye-mask concept was dropped due to the possibility that with equalizing receivers, the transmitter eye could be closed and still yield a working link. The eye mask would not be a reliable indicator of acceptable transmitter performance. This is not true for Open Eye transmitters, as there is no assumption that the receiver will be able to compensate for a closed eye transmitter. The first PAM-4 optical transmitter mask has been implemented in the Open Eye specification.

In addition to having mask polygons for three 'eyes' there are some important difference in the Open Eye mask method compared to legacy NRZ methods. First, the intent of the Open Eye mask is to limit deterministic eye closure, overshoot, and undershoot. Random jitter and noise are intentionally removed from the oscilloscope waveform through trace averaging. Second, NRZ mask tests typically employ a 'hit ratio' method where a small percentage of samples are allowed to violate the mask. This is important for test repeatability and to prevent a measurement that is highly dependent on observation time, as the likelihood of observing statistical outliers increases as more waveforms are observed. Because the Open Eye mask is configured to observe only deterministic signal features, it is not subject to statistical outliers. The Open Eye mask does not allow any mask hits.

The open eye mask dimensions are designed to graphically verify conformance to the vertical and horizontal eye opening requirements. An example of the Open Eye mask test was shown earlier in Figure 2.

5.4 Open Eye Reference Receiver

The Open Eye MSA reference receiver is designed for ease of testing and design. Figure 5 shows a block diagram of the test setup for the Open Eye Tx output testing and does not include virtual receiver equalization required for TDECQ. The optimization of the receiver equalization is not trivial and is difficult to speed up.

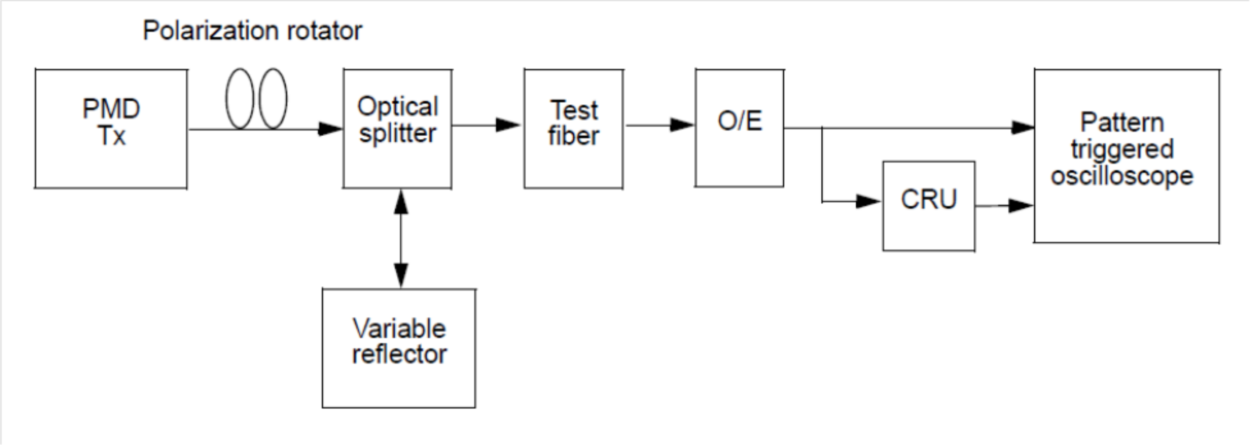


Figure 5 Open Eye MSA Tx test set up

6 Latency Benefits of Open Eye Optical Modules

As has been previously mentioned, the Open Eye approach allows for different technologies to be used to allow optimal performance in different applications. For some applications, latency is a key metric to be optimized and the Open Eye approach allows low latency, analog technologies to offer a key advantage.

Computing innovation has improved the speed of HPC, AI and Cloud computing over 100x by moving from CPU to GPU to AI chips. Similarly, memory access latency has also reduced by moving from HD to SSD to SCM/PMEM (See Figure 6).

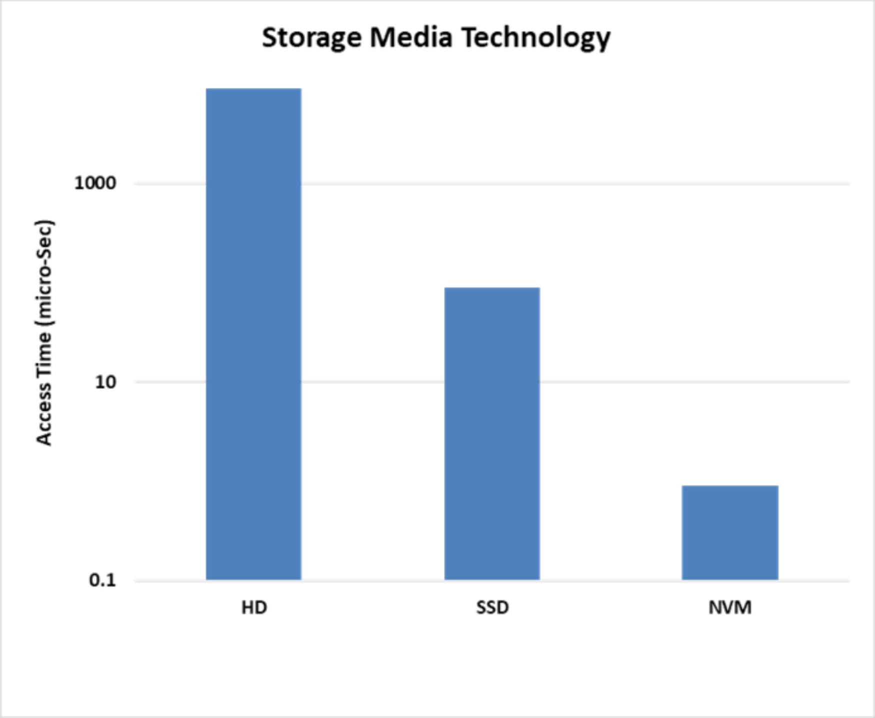


Figure 6 Improvements in memory access latency

Network bandwidths have also increased by the same 100x but the latency of these network connections has increased due to the use of DSP technology and FEC (Forward Error Correction). Figure 7 shows the latency of a DSP based solution compared to an analog-based Open Eye solution.

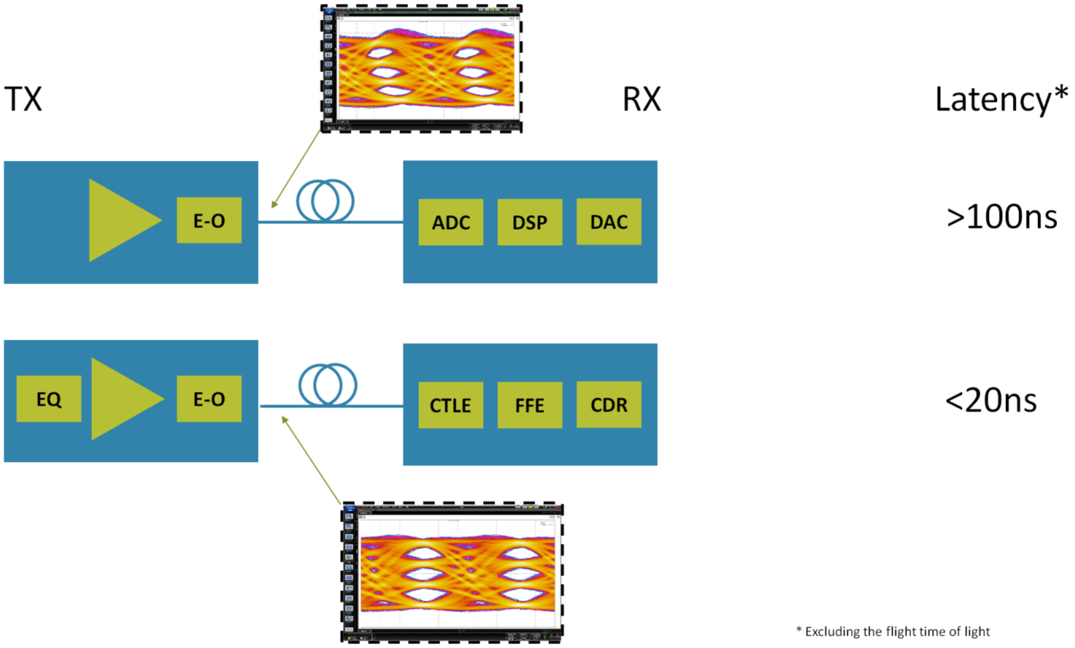


Figure 7 Latency comparison of a DSP based optical module vs. analog Open Eye module

In high performance computing (HPC), the links are kept short to minimize time of flight which reduces the latency. To see the effect on the network of the reduced latency of the Open Eye enabled solution we need to consider the latency of the various elements that make up the link including the server port and switch port. Figure 8 shows the latency of a typical Mellanox switch and server used in a HPC environment.

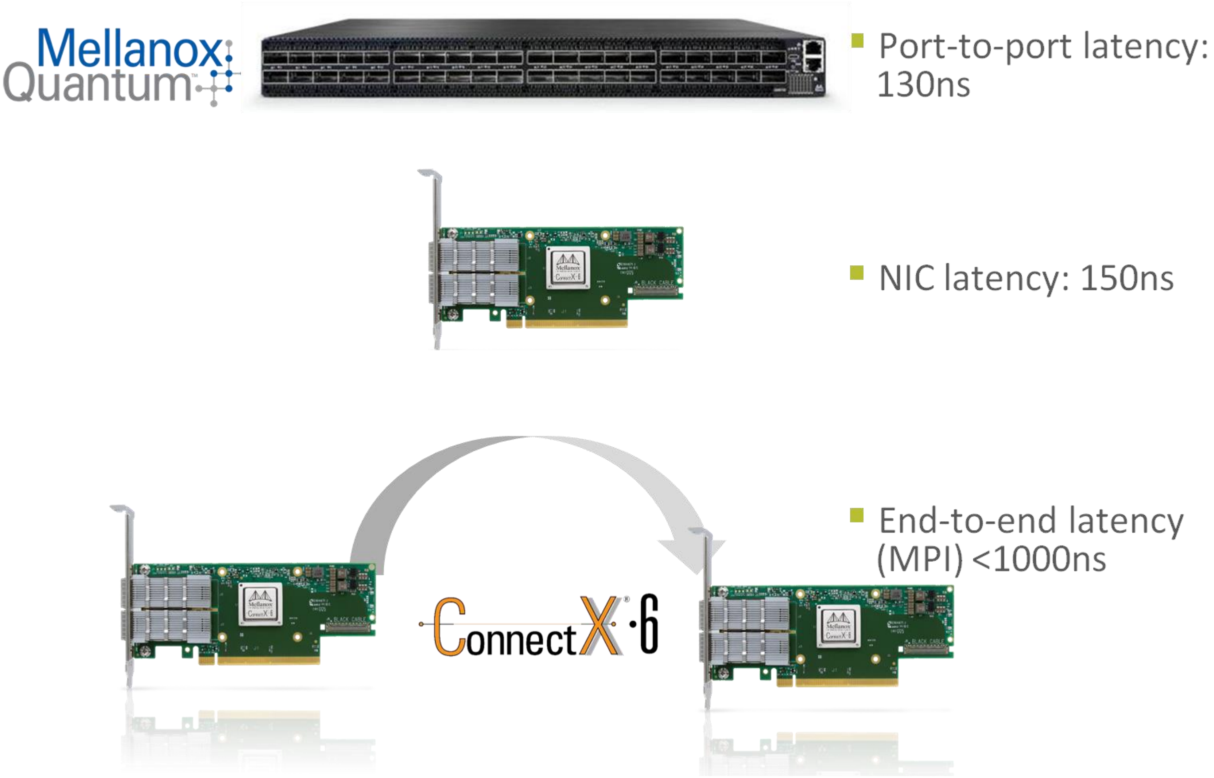


Figure 8 Network element latency in a HPC environment (Courtesy of Mellanox)

In a single node network hop, the use of analog Open Eye modules would result in a reduction of network transit time of 160ns compared to the latency of DSP-based modules. This is a 25% reduction in end–to–end latency.

In a data center application, the number of links required to achieve a connection can be greater. Figure 9 shows the different paths that could be taken in a data center and the number of links required to achieve these connections (each arrow is a link). Figure 10 shows the reduction in latency obtained by using analog Open Eye modules in a network.

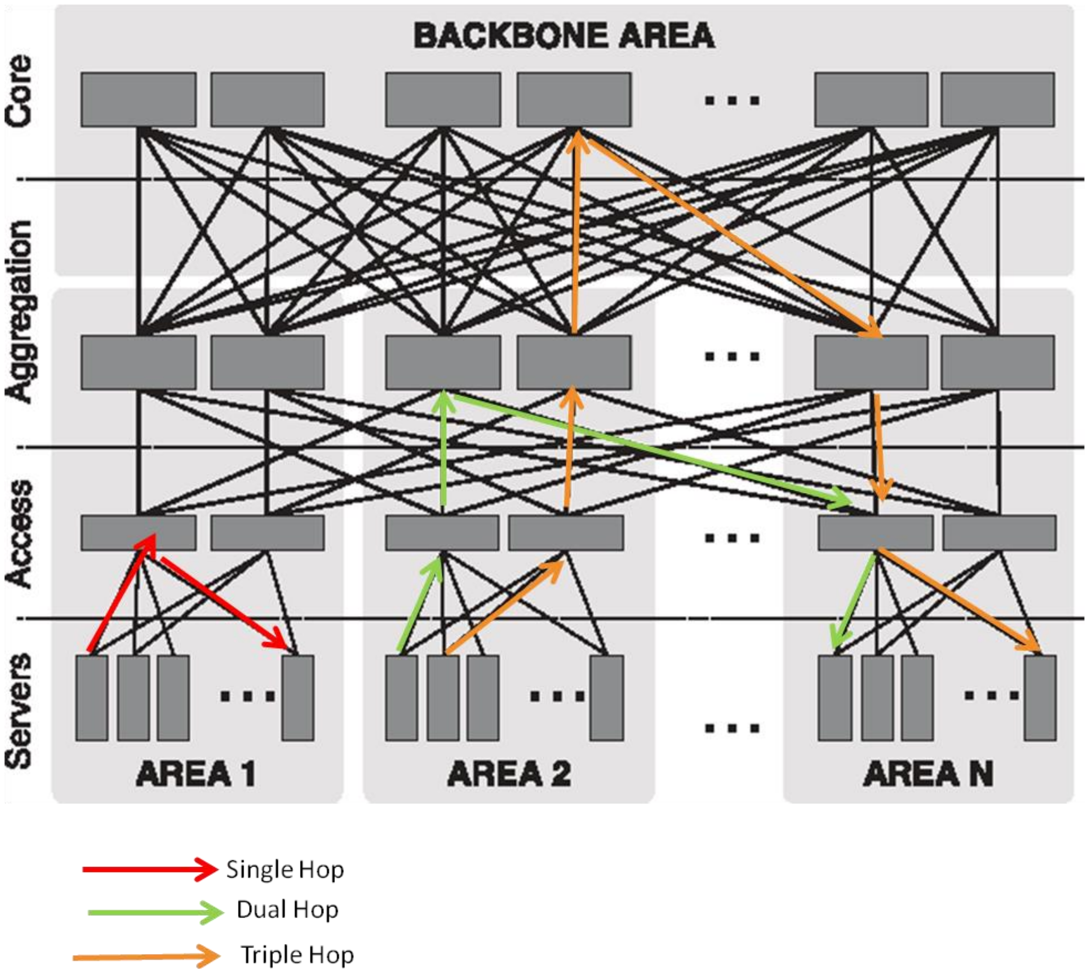


Figure 9 Types of data center connections

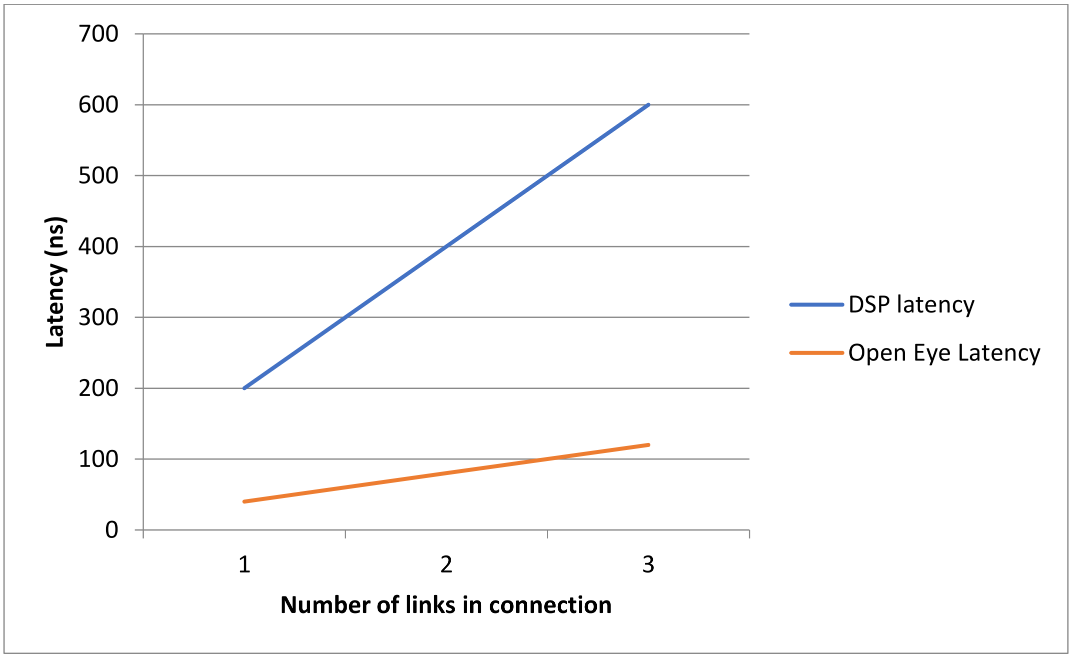


Figure 10 Latency reduction obtained using analog Open Eye modules

In this section, we have briefly shown that the Open Eye approach of separating transmitter optimization from receiver optimization allows a different technology choice to optimize for low latency. An analog Open Eye MSA based optical module provides the lowest latency optical interconnect for AI and HPC applications. It has been proposed in literature that future data centers will care about latency as much as the HPC community. The Open Eye MSA will allow solutions for these low latency data center applications such as data translation. In addition, 5G applications such as support for autonomous vehicles will benefit from the low latency technology that an Open Eye MSA based optical module can provide.

7 Summary

This paper has shown how the Open Eye approach benefits users by allowing greater technology selection in their optical module designs. This enables users to optimize their design for cost, power and latency in ways that have not been available previously at 50 Gb/s. We have also shown that separating the transmitter equalization from the receiver equalization results in reduced design complexity (via use of different technologies) and reduced test time (by elimination of TDECQ equalizer optimization) whilst still maintaining an IEEE compatible link budget.

The Open Eye MSA was formed with the goal of simplifying the industry standard optical specifications to enable high performance optical modules with reduced power, lower latency, wider technology selection and lower cost. The Open Eye MSA and its 35+ industry leading members comprising silicon, module, system and test companies contributed to this white paper with analysis, simulation and test results.

Participants in the MSA include Clock and Date Recovery (CDR) IC suppliers, optical module suppliers and system developers. The MSA specifications will support both existing module types (SFP, QSFP) and higher density emerging module types (SFP-DD, DSFP, QSFP-DD, OSFP, Co-packaged Optics).