

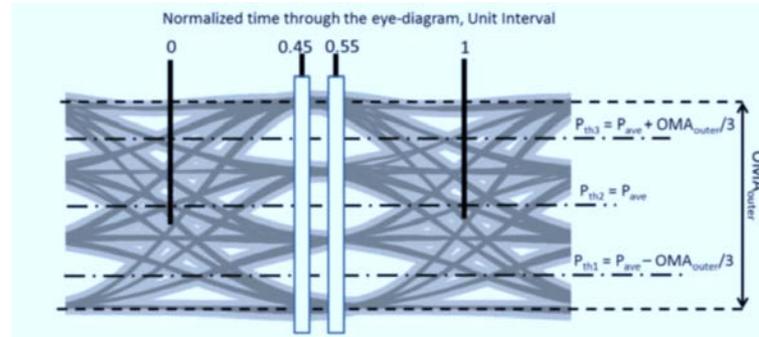
TDEC for PAM4 ('TDECQ')

Changes to clause 123, to replace TDP with TDECQ
rev 1a

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Proposal for TDEC for PAM4 signals -1



- Scope based, TDEC variant, expanded for all three sub-eyes in an equalized PAM4 signal
- Reference receiver and equalizer are software based 'in the 'scope'
- Single timing position in centre of eye for all three sub-eyes, +/-0.05 UI (TBC)
- TDECQ calculated from fixed thresholds: P_{ave} , $P_{ave} + OMA/3$, $P_{ave} - OMA/3$
 - Penalizes transmitters which have unequal sub-eyes
 - Not how a 'real' PAM4 retimer is expected to work, but avoids the issue of how to measure accurately the penalty of unequal sub-eyes when received by a 'real' receiver, which may have differing sensitivities for each sub-eye.
 - Should 400GE decide that optimized thresholds should be specified for the TDECQ test, an additional (non-trivial) test will be needed to measure how transmitter and receiver sub-eye inequality/non-linearity interact.

Proposal for TDEC for PAM4 signals -2

- Conceptual basics
 - Measure scope noise without signal, σ_s
 - Measure histogram through equalized eye to be tested, normalize
 - Equalization is done in the 'scope with a ref. equalizer (e.g. 5 T/2 tap FFE)
 - This represents the vertical probability density function (PDF) through the PAM4 eye
 - Do this for left and right of eye time centre
 - From the vertical PDF through the PAM4 eye, create 3 cumulative probability functions, one around each sub-eye threshold.
 - Add normalized Gaussian noise term σ_G to the sub-eye thresholds
 - to create 3 PDFs consisting of a Gaussian PDF centred around each sub-eye thresholds
 - Multiply each threshold PDF by the appropriate cum've eye PDF to calculate a proxy for SER for that threshold; sum the results
 - Find smallest size of σ_G that makes resultant = target SER
 - TDECQ is given by:

$$TDECQ = 10 \cdot \log_{10} \left(\frac{OMA}{6} \times \frac{1}{Q_t R} \right)$$

where Q_t is the Q function value consistent with the target symbol error ratio,

$$R = (C_{eq} \sigma_G^2 + \sigma_s^2)^{1/2},$$

and C_{eq} is a coefficient which accounts for the reference equalizer noise enhancement factor when the equalizer has been optimized for minimum TDECQ.

Changes to 400GBASE-FR8 and -LR8 (Clause 123)

- The following slides show draft changes to clause 123 needed to introduce TDECQ and SECQ (for SRS test source calibration).

Changes to section 123.8.5

Transmitter and dispersion eye closure

- *Paraphrased text in clause 95.8.5, with reference to appropriate tables*
 - *use a worst case fibre for longwave, use a reduced bandwidth (TBD) Rx for SR, mention reference equalizer.*

123.8.5 Transmitter and dispersion eye closure for PAM4 (TDECQ)

TDECQ of each lane shall be within the limits given in Table 123-xxx if measured using the methods specified in 123.8.5.1, 123.8.5.2, and 123.8.5.3..

TDECQ is a measure of each optical transmitter's vertical eye closure when transmitted through a worst case optical channel (specified in 123.8.5.2), as measured through an optical to electrical converter (O/E) with a bandwidth equivalent to a reference receiver, and equalized with the reference equalizer (as described in 123.8.5.4). The reference receiver and equalizer may be implemented in software or may be part of the oscilloscope.

Table 123-11 specifies the test patterns to be used for measurement of TDECQ.

- *3 more sub-sections need to be added one before, two after sub-section 123.8.5.1 (which describes worst case optical channel) to describe the measurement set up, TDEC calculation method, and reference equalizer.*
- *SRS sub-sections need to be populated*

New section: 123.8.5.1 TDECQ test set up

123.8.5.1 TDECQ conformance test setup

A block diagram for the TDECQ conformance test is shown in Figure 123-4. Other equivalent measurement implementations may be used with suitable calibration.

Each optical lane is tested individually with all other lanes in operation. The optical splitter and variable reflector are adjusted so that each transmitter is tested with the optical return loss specified in Table 123-12. The state of polarization of the back reflection is adjusted to create the greatest RIN. The optical filter is used to separate the lane under test from the others. Each optical lane is tested with the optical channel described in 123.8.5.2. The combination of the O/E and the oscilloscope has a fourth-order Bessel-Thomson filter response with a bandwidth of 19.34 GHz. Compensation may be made for any deviation from an ideal fourth-order Bessel-Thomson response.

The optical filter passband ripple shall be limited to 0.5 dB peak-to-peak and the isolation is chosen such that the ratio of the power in the lane being measured to the sum of the powers of all of the other lanes is greater than 20 dB (see ITU-T G.959.1 Annex B).

The test pattern (specified in Table 123-11) is transmitted repetitively by the optical lane under test and the oscilloscope is set up to capture the complete pattern for TDECQ analysis as described in 123.8.5.3.

The clock recovery unit (CRU) has a corner frequency of 4 MHz and a slope of 20 dB/decade. The CRU can be implemented in hardware or software depending on oscilloscope technology.

New section: 123.8.5.1 TDECQ test set up

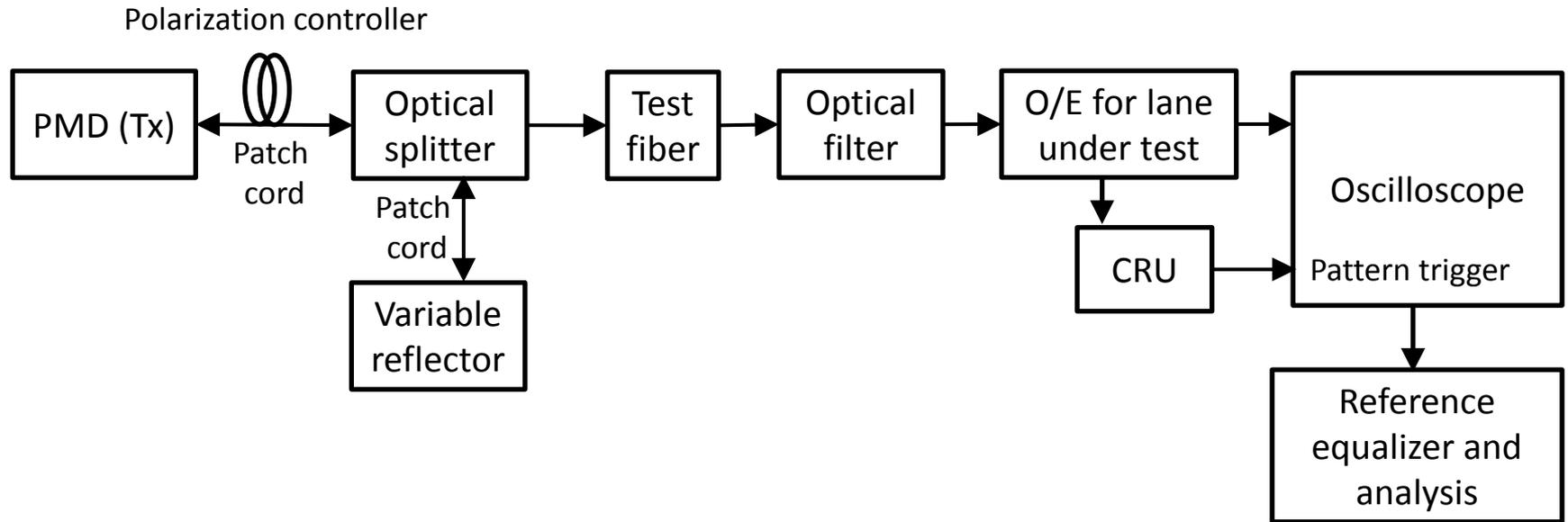


Figure 123-4 — TDECQ conformance test block diagram

JPK note: The optical filter is removed for DR4

New section 123.8.5.3 TDECQ measurement method

123.8.5.3 TDECQ measurement method

The standard deviation of the noise of the O/E and oscilloscope combination, σ_S , is determined with no optical input signal and the same settings as used to capture the histograms described below.

OMA_{outer} is measured according to 123.8.4.

The test pattern specified for TDECQ (see Table 123-11) is transmitted repetitively by the optical lane under test and the oscilloscope is set up to capture samples from all symbols in the complete pattern.

The reference equalizer (specified in 123.8.5.4) is used to optimize the signal-to-noise ratio of the captured waveform (to minimize the value of TDECQ), and the tap coefficients of the optimized reference equalizer are recorded.

If a sampling oscilloscope is used, the impact of the sampling process and the reference equalizer on transmitter noise must be compensated for, so that the correct magnitude of noise is present at the output of the equalizer. A reconstructed eye diagram is formed from the optimally equalized captured pattern.

If a real time sampling scope is used, and the reference equalizer is implemented in the oscilloscope, then the oscilloscope can be set up to capture an eye diagram directly.

The average optical power (P_{ave}) of the eye diagram is determined, and the 0 UI and 1 UI crossing points are determined by the average of the eye diagram crossing times, as measured at P_{ave} , as illustrated in Figure 123-5.

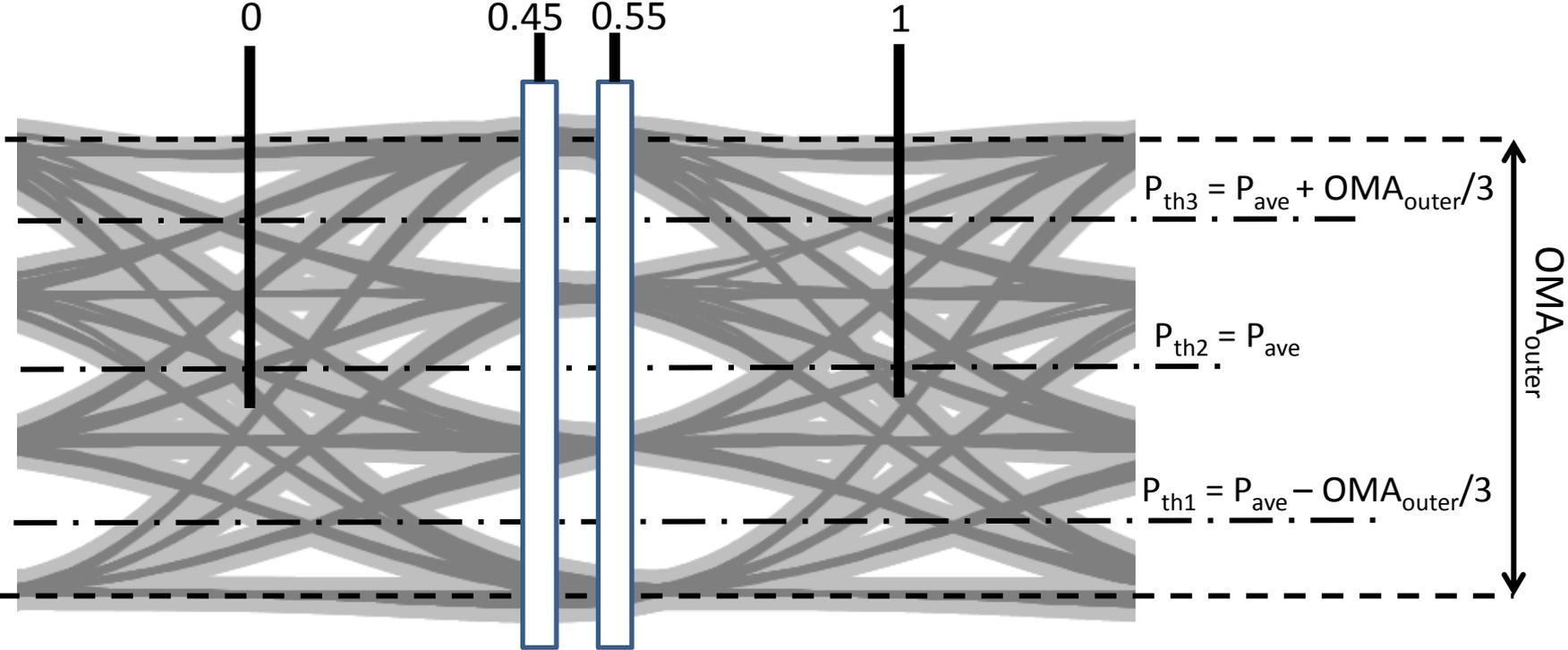
Two vertical histograms are measured through the eye diagram, centered at 0.45 UI and 0.55 UI, each of the histograms spans all of the modulation levels of the eye diagram, as illustrated in Figure 123-5.

Each histogram window has a width of 0.04 UI. Each histogram window has outer height boundaries which are set beyond the extremes of the eye diagram (so that no further samples would be captured by increasing the vertical separation of the height boundaries).

cont'd....

Figure 123-5 Illustration of the TDECQ measurement

Normalized time through the eye-diagram, Unit Interval



123.8.5.3 TDECQ measurement method... cont'd

The sub-eye threshold levels P_{th1} , P_{th2} , and P_{th3} are determined from the OMA_{outer} and the average optical power of the eye diagram, P_{ave} , as follows:

$$P_{th1} = P_{ave} - \frac{OMA_{outer}}{3}$$

$$P_{th2} = P_{ave}$$

$$P_{th3} = P_{ave} + \frac{OMA_{outer}}{3}$$

Each captured histogram is processed to convolve the PAM4 eye with the reference receiver noise, in order to produce an estimate of the partial symbol error ratio (SER) for each sub-eye; one way of doing this is described below.

The histogram is normalized, and can be represented as a series of equally spaced optical power values (y_i) with separation Δy , each with an associated fraction $f(y_i)$, equal to the number of samples captured in that power interval divided by the total number of samples in the histogram. The sum of all $f(y_i)$ is equal to 1.

From the normalized histogram $f(y_i)$, three cumulative probability functions are created, $Cf_1(y_i)$, $Cf_2(y_i)$, and $Cf_3(y_i)$, one around each sub-eye threshold. For example:

$$Cf_1(y_i) = \sum_{y=P_{th1}}^{y_i} |(f(y_i) - f(P_{th1}))|$$

Each element of the cumulative probability function $Cf_1(y_i)$ is multiplied by a value $G_{th1}(y_i)$, and then summed to calculate an approximation for the partial symbol error ratio (SER) for threshold 1. $G_{th1}(y_i)$ is equivalent to a Gaussian probability density function with an RMS value of σ_G , centered around the sub-eye threshold P_{th1} . $G_{th1}(y_i)$ is given by:

$$G_{th1}(y_i) = \frac{2}{3} \cdot \frac{1}{\sqrt{2\pi}} \cdot e^{-\left(\frac{y_i - P_{th1}}{\sigma_G}\right)^2} \cdot \Delta y$$

123.8.5.3 TDECQ measurement method... cont'd

The other two cumulative probability functions $Cf_2(y_i)$ and $Cf_3(y_i)$ are treated similarly, to find the partial SER for threshold 2 and threshold 3.

The smallest size of σ_G is found that makes the sum of the partial SERs equal to the target SER = 4.8×10^{-4} for either left or right histogram.

The noise, R, that could be added by a receiver is

$$R = (C_{eq}\sigma_G^2 + \sigma_S^2)^{1/2}$$

where C_{eq} is a coefficient which compensates for the reference equalizer noise enhancement factor when the equalizer has been optimized for minimum TDECQ. The value of C_{eq} can be calculated from the product of the noise power density spectrum $N(\omega)$ at the input of the reference equalizer, and the frequency response $S_{eq}(\omega)$ of the optimized reference equalizer:

$$\frac{1}{C_{eq}} = \int^{\omega} N(\omega) \cdot S_{eq}(\omega) \cdot d\omega$$

where the noise power density spectrum $N(\omega)$ is equivalent to white noise filtered by a fourth-order Bessel-Thomson response filter with a bandwidth of 19.34 GHz.

TDECQ is given by:

$$TDECQ = 10 \cdot \log_{10} \left(\frac{OMA_{outer}}{6} \times \frac{1}{Q_t R} \right)$$

where $Q_t = 3.414$ consistent with the BER and target symbol error ratio for Gray coded PAM4.

123.8.5.4 TDECQ reference equalizer

123.8.5.4 TDECQ reference equalizer

The reference equalizer for 400GBASE-FR8 and 400GBASE-LR8 is a 5 tap, T/2 spaced, feed-forward equalizer (FFE).

Changes to Table 123-7, Table 123-8, Table 123-9, and Table 123-10 and Table 123-11

- Change "TDP" to "TDECQ" in Table 123-7 and Table 123-9
- Change "Stressed receiver sensitivity (OMA_{inner}), each lane (max)" to "Stressed receiver sensitivity (OMA_{outer}), each lane (max)" in Table 123-8 with a value equal to $(OMA_{outer} - TDECQ)$ (min) - channel insertion loss + TDECQ (max)
- Change "Condition 1" to "SECQ" in Table 123-8 with a value equal to the TDECQ value from Table 123-7
- Change "Condition 2" to " OMA_{outer} of each aggressor lane" in Table 123-8 with a value equal to OMA_{outer} (min) + difference in launch power between any two lanes (max)
- Remove "Calibration of OMA for receiver tests" row from Table 123-11
- Change "TDP" to "TDECQ" in Table 123-11, add test pattern number for SSPRQ shown in Table 123-10, and add SSPRQ test pattern to Table 123-10
- Remove Transmitter eye mask definition from Table 123-7.
- Remove 123.8.8

SRS test sections

- Work in progress...
 - SECQ is same metric as TDECQ but without worst case fibre
 - SECQ spec value is same as TDECQ spec value but without w/c fibre
 - SRS test description follows clause 95 SRS description with necessary changes

SRS test 123.8.10

123.8.10 Stressed receiver sensitivity

Stressed receiver sensitivity shall be within the limits given in Table 123–8 if measured using the method defined by 123.8.10.1 and 123.8.10.3, with the conformance test signal at TP3 as described in 123.8.10.2, using the test pattern specified for SRS in Table 123–11. The BER is required to be met for the lane under test on its own.

Stressed receiver sensitivity is defined with all transmit and receive lanes in operation. Any of the patterns specified for SRS in Table 123-11 is sent from the transmit section of the PMD under test. The signal being transmitted is asynchronous to the received signal.

SRS test: 123.8.10.1

123.8.10.1 Stressed receiver conformance test block diagram

A block diagram for the receiver conformance test is shown in Figure 123–6. The patterns used for the stressed receiver conformance signal are specified in Table 123–11. The optical test signal is conditioned (stressed) using the stressed receiver methodology defined in 123.8.10.2 and has sinusoidal jitter applied as specified in 123.8.10.4.

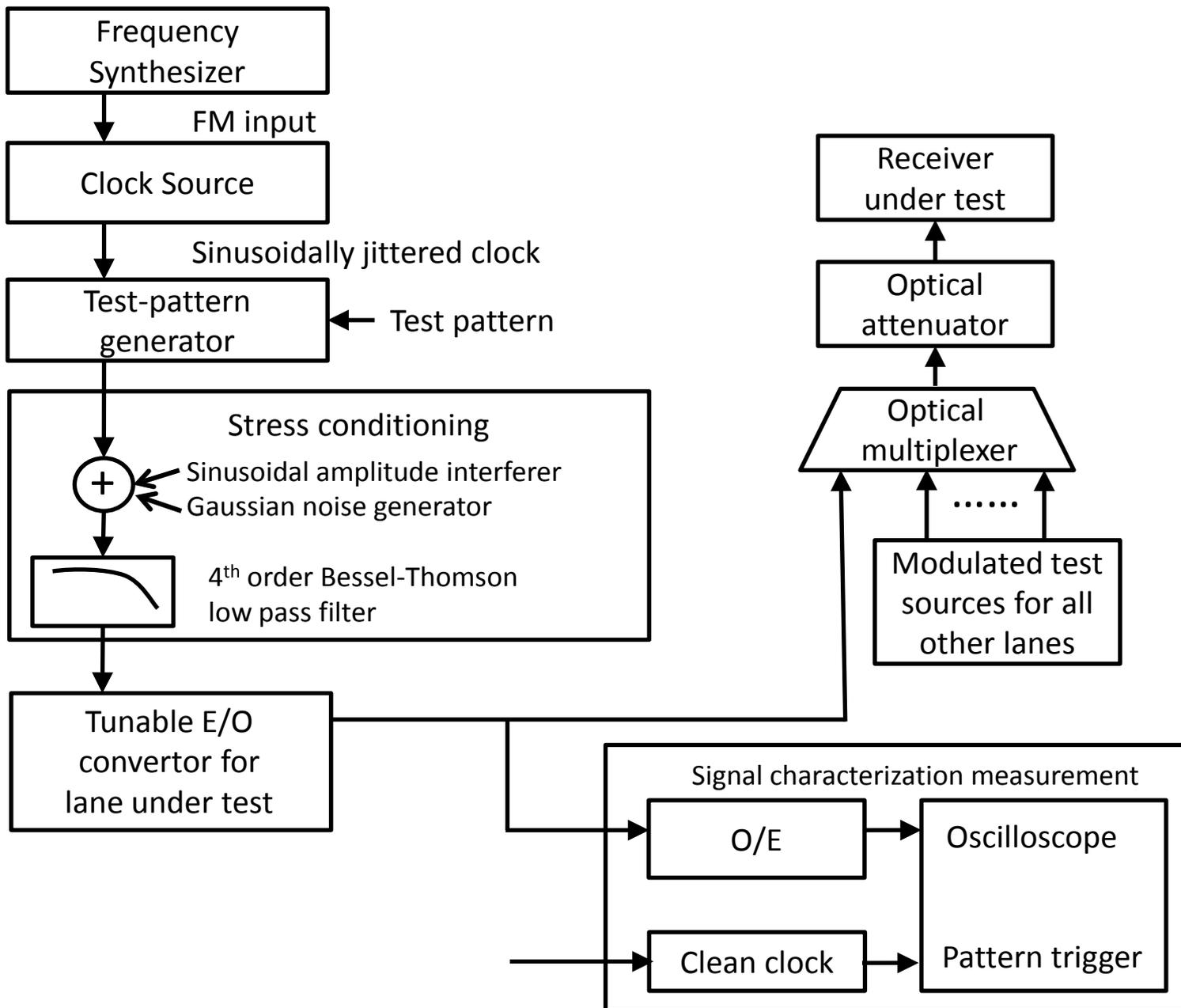
A suitable test set is needed to characterize the signal used to test the receiver. Stressed receiver conformance test signal verification is described in 123.8.10.3.

The fourth-order Bessel-Thomson low-pass filter is used to create ISI. The combination of the low-pass filter and the E/O converter should have a frequency response that results in at least two thirds of the dB value of the stressed eye closure (SECQ) specified in Table 123-8 before the sinusoidal and Gaussian noise terms are added, according to the methods specified in 123.8.10.3. The sinusoidal amplitude interferer causes additional eye closure, but in conjunction with the finite edge rates, also causes some jitter.

The sinusoidally jittered clock represents other forms of jitter and also verifies that the receiver under test can track low-frequency jitter. The sinusoidal amplitude interferer may be set at any frequency between 100 MHz and 2 GHz, although care should be taken to avoid harmonic relationships between the sinusoidal interferer, the sinusoidal jitter, the signaling rate, and the pattern repetition rate. The Gaussian noise generator, the amplitude of the sinusoidal interferer, and the low-pass filter are adjusted so that the SECQ specified in Table 123–8 is met, according to the methods specified in 123.8.10.3.

For improved visibility for calibration, all elements in the signal path (cables, DC blocks, E/O converter, etc.) should have wide and smooth frequency response, and linear phase response, throughout the spectrum of interest. Baseline wander and overshoot and undershoot should be minimized.

Figure 123-6 —Stressed receiver conformance test block diagram



SRS test: 123.8.10.2

123.8.10.2 Stressed receiver conformance test signal characteristics and calibration

The conformance test signal is used to validate that each lane of the PMD receiver meets BER requirements with near worst-case waveforms at TP3.

The primary parameters of the stressed receiver conformance test signal are its stressed eye closure (SECQ), and the sinusoidal jitter applied, as specified in 123.8.10.4. The SECQ of the stressed receiver conformance test signal is measured according to 123.8.5, except that the polarization controller, optical splitter, variable reflector, and the test fiber, are not used. An example stressed receiver conformance test setup is shown in Figure 123–6; however, alternative test setups that generate equivalent stress conditions may be used.

The following steps describe a possible method for setting up and calibrating a stressed receiver conformance test signal when using a stressed receiver conformance test setup as shown in Figure 123–6:

- 1) Set the signaling rate of the test pattern generator to meet the requirements in Table 123–7.
- 2) With the sinusoidal jitter, sinusoidal interferer, and the Gaussian noise generator turned off, set the extinction ratio of the E/O to approximately the minimum specified in Table 123–7.
- 3) The required value of SECQ is given in Table 123–8. With the sinusoidal jitter, sinusoidal interferer, and Gaussian noise generator turned off, at least two thirds of the dB value of SECQ should be created by the selection of the appropriate bandwidth for the combination of the low-pass filter and the E/O converter. Any remaining SECQ must be created with a combination of sinusoidal jitter, sinusoidal interference, and Gaussian noise. Sinusoidal jitter is added as specified in Table 123–13.

SRS test: 123.8.10.2 continued

123.8.10.2 Stressed receiver conformance test signal characteristics and calibration ... cont'd

When calibrating the conformance signal, the sinusoidal jitter frequency should be between 50 MHz and 10 times LB as defined in Table 123–13. Sinusoidal jitter amplitude may be calibrated by measuring the jitter on the oscilloscope, while transmitting the square wave pattern, and using a clean clock in place of the CRU to trigger the oscilloscope.

Iterate the adjustments of the sinusoidal interferer, the Gaussian noise generator, and extinction ratio, until the required value of SECQ is met, while also meeting the following conditions: the extinction ratio is approximately the minimum specified in Table 123–7; and sinusoidal jitter is as specified in Table 123–13.

Each receiver lane is conformance tested in turn. The source for the lane under test is adjusted to supply a signal at the input to the receiver under test at the “Stressed receiver sensitivity (OMA_{outer}), each lane (max)” specified in Table 123–8, and the test sources for the other lanes are set to the “ OMA_{outer} of each aggressor lane” specified in Table 123–8.

SRS test 123.8.10.3

123.8.10.3 Stressed receiver conformance test signal verification

The SECQ of the stressed receiver conformance test signal is measured according to 123.8.5, except that the test fiber is not used. The clock output from the clock source in Figure 123–6 is modulated with the sinusoidal jitter. To use an oscilloscope to calibrate the final stressed eye jitter that includes the sinusoidal jitter component, a separate clock source (clean clock of Figure 123–6) is required that is synchronized to the source clock, but not modulated with the jitter source.

Care should be taken when characterizing the test signal because excessive noise/jitter in the measurement system would result in an input signal that does not fully stress the receiver under test. Running the receiver tolerance test with a signal that is under-stressed may result in the deployment of non-compliant receivers. Care should be taken to minimize the noise/jitter introduced by the O/E, filters, and oscilloscope, and/or to correct for this noise. While the details of a BER scan measurement and test equipment are beyond the scope of this standard, it is recommended that the implementer fully characterize the test equipment and apply appropriate guard bands to ensure that the stressed receiver conformance input signal meets the stress and sinusoidal jitter specified in 123.8.10.2 and 123.8.10.4.

SRS test 123.8.10.4

123.8.10.4 Sinusoidal jitter for receiver conformance test

The sinusoidal jitter is used to test receiver jitter tolerance. The amplitude of the applied sinusoidal jitter is dependent on frequency as specified in Table 123–13 and is illustrated in Figure 123-7.

Table 123-13 Applied sinusoidal jitter

Frequency	Sinusoidal jitter, peak-to-peak (UI)
$f < 40 \text{ kHz}$	Not specified
$40 \text{ kHz} < f \leq 4 \text{ MHz}$	$2 \times 10^5 / f$
$4 \text{ MHz} < f < 10 \text{ LB}^a$	0.05

^aLB = loop bandwidth; upper frequency bound for added sine jitter should be at least 10 times the loop bandwidth of the receiver being tested.

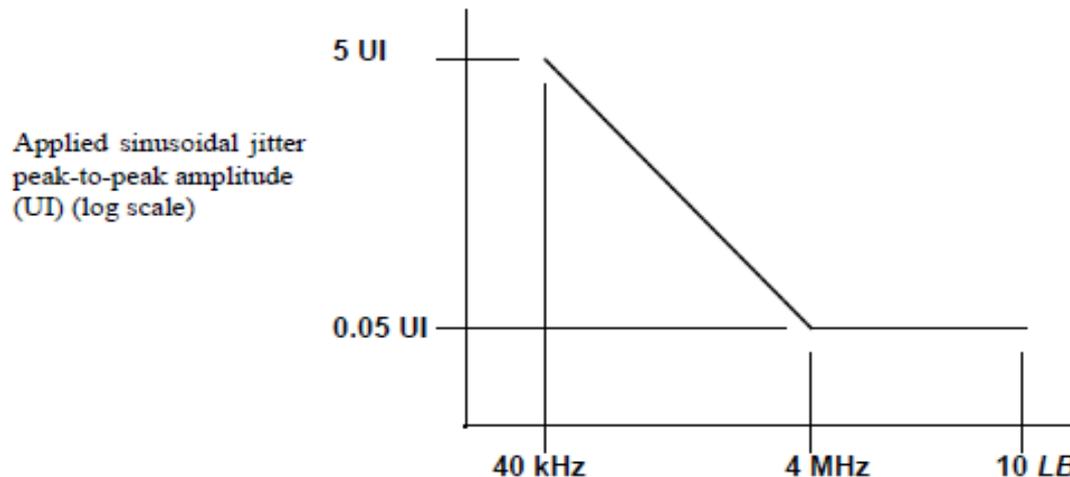


Figure 123-7 Illustration of the mask of the sinusoidal component of jitter tolerance

Changes to 123.10 and PICS

- Table 123-13 becomes Table 123-14 (after insertion of Table 'Applied sinusoidal jitter')
- 123.12.4.5
 - OM5: replace TDP with TDECQ

Q & A

thanks !