40GBASE-SR4 & 100GBASE-SR10 Link Model Update & Review

John Petrilla,

Avago Technologies

May 2009

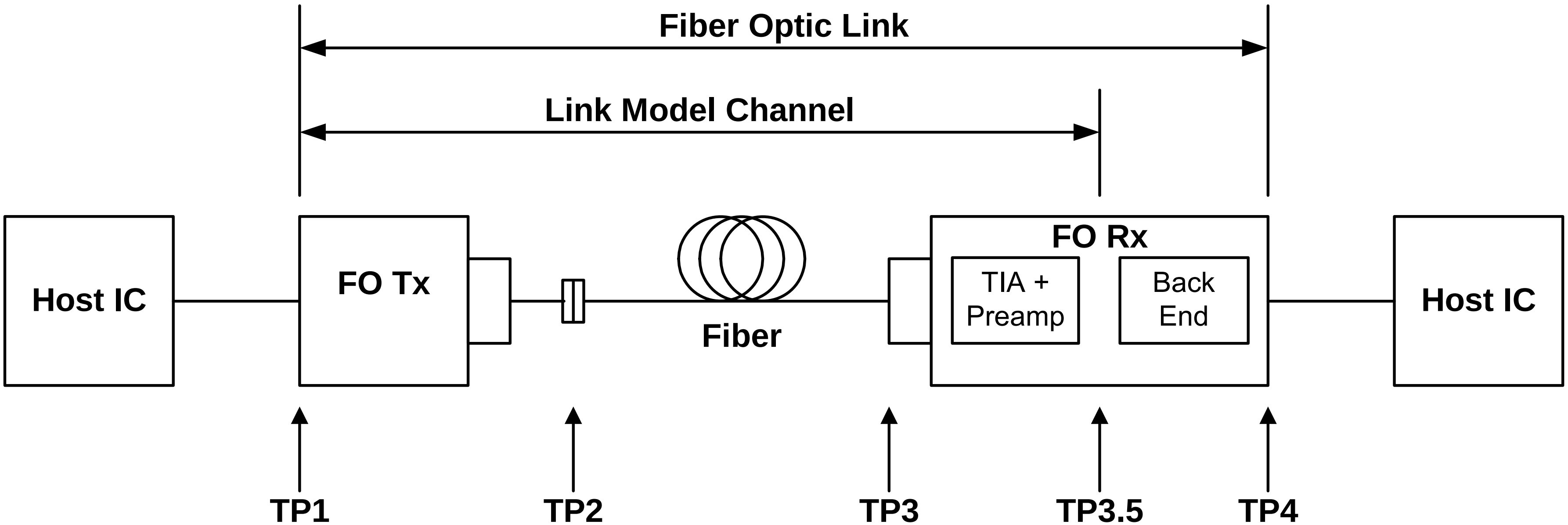
Presentation Overview

- Baseline model with updates for D2.0 & J2
- Min Pave, Max OMA & Peak Po determination
- TDP determination & sensitivities
- SRS determination
- Eye Masks
- Link Model background

Systematic Approach Proposition

- Jitter Allocation: An extended 10GbE link model can be used to convert noise penalties into jitter at each interface of interest. See petrilla_02_1108. This reconciles jitter allocations with power penalties and provides a consistent allocation approach that enables balancing the burden at the various interfaces. It also permits a more appropriate determination of the jitter used for stressed receiver test set-ups.
- Eye Mask: An extended 10GbE link model can be used to define Tx eye masks that ensure better than required signal characteristics at Rx inputs while minimizing unneeded burdens. See petrilla_03_1108. By only requiring what is needed by the downstream receiver, neither the Tx nor the Rx face an unnecessary or disproportionate burden.
- Jitter, being one-dimensional, permits easier de-embedding of test equipment artifacts than the two-dimensional nature of eye displays. Consequently, while jitter specifications can be written without including consideration of test artifacts, it appears advantageous to define mask coordinates with a minimum performance level reference test system.
- Herein, for eye diagrams, as an example of a minimum performance reference test system, a sampling scope was assumed with a timing uncertainty of 0.2 ps RMS, electrical sensitivity and BW that provide no significant impairment and an optical sensitivity of -14.5 dBm and BW of 7.5GHz. A BW requirement for an eye mask tests is already common practice.

Link Model Definition



- Fiber optic link and component specifications are often based on a link definition similar to that shown above. Shown in the above figure are functional link blocks and interfaces between blocks. In general, for standards, specifications apply at the interfaces. This can provide the basis for inter-operability among independently produced components.

- Ethernet has used the terms TP1, TP2, TP3 & TP4 for the interfaces. TP3.5 is added to represent better the decision point, that is, the end of the channel for the 10GbE model where penalty accounting is performed.

40GBASE-SR4 & 100GBASE-SR10 Base Case

Link Model Transmitter Attributes (Each Lane)

Min Center Wavelength: **840 nm**

Max RMS Spectral Width: **0.65 nm**

Min OMA: **-3 dBm @ max TDP**

Max TDP: **4 dB**

Min ER: **3 dB**

Max Transition Time (20%, 80%): 35.6 ps

Max RIN12OMA: -130 dB/Hz

RIN Coefficient: 0.70

Mode Partition Noise Coefficient: 0.30

TP1 Jitter Allocation: DDPWS = **0.07 UI**, **J2 = 0.18 UI**, **J9 = 0.26 UI**, TJ = 0.281 UI

TP1 Eye Mask Coordinates X1, X2, Y1, Y2: **0.1 UI, 0.31 UI, 95 mV, 350 mV**

TP2 Jitter Model: J2 = 0.334 UI, J9 = 0.442, TJ = 0.470 UI

TP2 Eye Mask Coordinates X1, X2, X3, Y1, Y2, Y3: = 0.23, 0.34, 0.43, 0.27, 0.33, 0.40

Bold font identifies normative requirement

40GBASE-SR4 & 100GBASE-SR10 Base Case

Link Model Receiver Attributes (Each Lane)

Stressed Rx Sensitivity: **-5.4 dBm**

- VECP: **2 dB**
- J2: **0.35 UI**
- J9: **0.47 UI**

Max Sensitivity: -11.3 dBm

Min Bandwidth: 7500 MHz

RMS Base Line Wander: 0.025

TP3 DCD Allocation: DCD = 0.103 UI

TP3 Jitter Model: J2 = 0.341 UI, J9 = 0.458 UI, TJ = 0.489 UI

TP4 Jitter Model: J2 = 0.46 UI, J9 = 0.63 UI, TJ = 0.676 UI

TP4 Eye Mask Coordinates X1, X2, Y1, Y2: = 0.29, 0.5, 150, 425

Bold font identifies normative requirement.

40GBASE-SR4 & 100GBASE-SR10 Base Case

Link Model Channel Attributes (Each Lane)

- Signal Rate: 10.3125 GBd
- **BER: < 10^{-12}** (Q = 7.034)
- **100 m of OM3**
- **1.5 dB connector loss allocation**
- Signal Power Budget: 8.3 dB
- Attenuation = 0.36 dB
- Center Eye Penalties
  - Pisi = 1.45 dB
  - Pdj = 0.14 dB
  - Pmn = 0.30 dB
  - Pmpn = 0.02 dB
  - Prin = 0.14 dB
  - Pcross = 0.13 dB

Bold font identifies normative requirement.

Jitter Model Results - Base Case (Dual-Dirac Model)

		TP1	TP2	TP3	TP4
J2*=[DJ(δδ)+ (2.807/Q_0)RJ]	UI	0.180 (**0.18**)	0.335	0.343 (**0.35**)	0.467 (**0.46**)
J9=[DJ(δδ)+ (6.219/Q_0)RJ]	UI	0.260 (**0.26**)	0.441	0.457 (**0.47**)	0.632 (**0.63**)
DDPWS	UI	(**0.07**)		0.103	
5E-5 (Q_5 = 3.8906)	UI	0.205	0.369	0.379	0.519
TJ (Q_0 = 7.034)	UI	0.279	0.466	0.485	0.671
DJ(δδ)	UI	0.114	0.248	0.248	0.331
RJ (Q_0 = 7.034)	UI	0.165	0.218	0.237	0.340

Base case has been updated for D2.0 TP1 allocations. Bold entries indicate normative requirements.

For all the interface points, as shown in the above table, the extended 10GbE link model can, from allocated dual-Dirac DJ and TP1 RJ, determine values for TJ, J9, J2* as well as the 5E-5 hit ratio proposed for eye masks. This systematic approach ensures consistency among the various interfaces and between the various jitter measures. The above values do not reflect any impairment due to test artifacts.

*High probability jitter, including J2, is not modeled well by dual-Dirac which may lead to overestimates of RJ and underestimates of DJ. In the above table, TP1 values for RJ and DJ(δδ) were calculated from the D2.0 J2 and J9 values. See next page for consequences of under estimating DJ(δδ) content in J2 by 25%.

Jitter Model Results - Base Case

(Modified J2 Dual-Dirac Model)

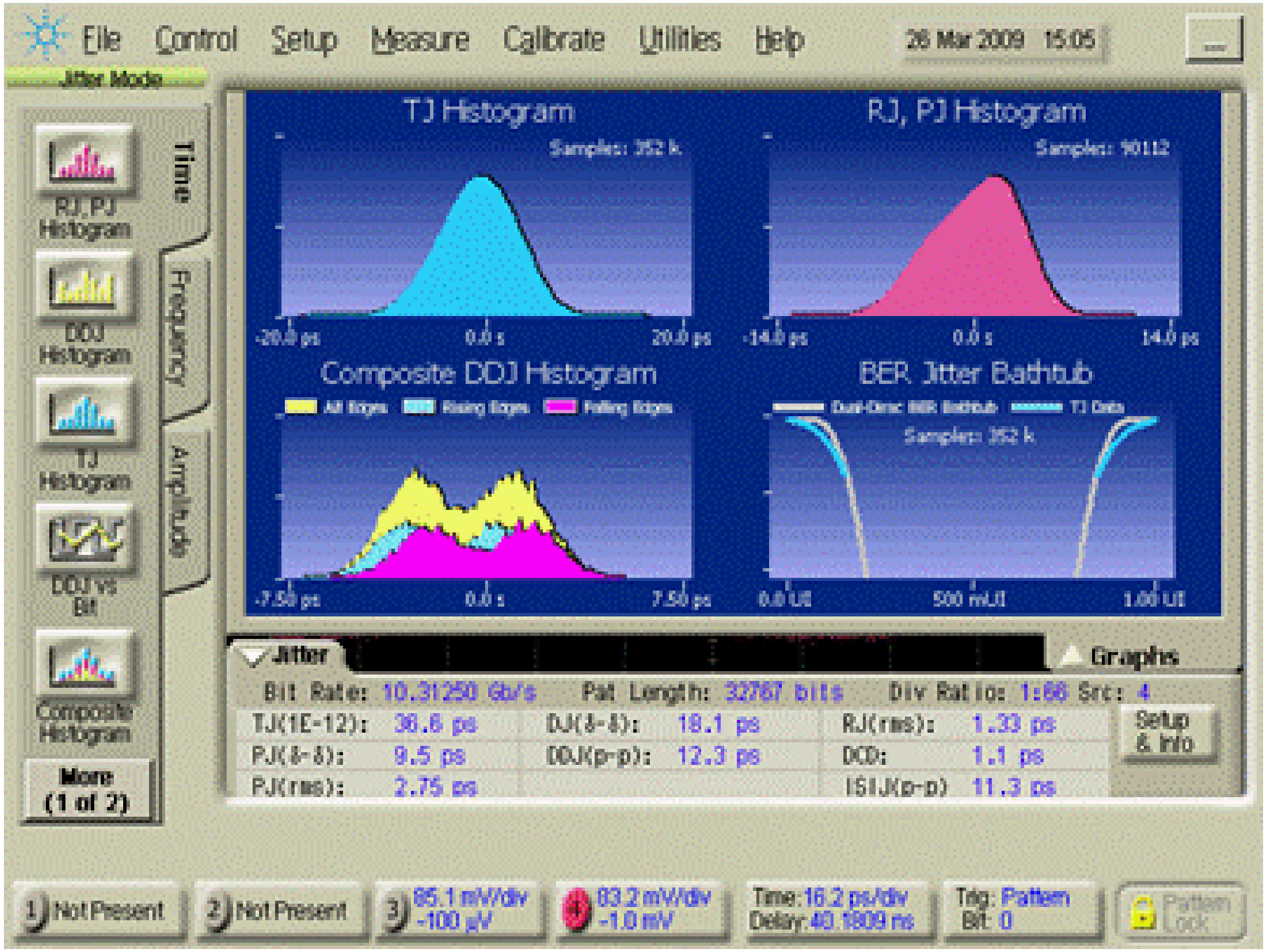
		TP1	TP2	TP3	TP4
J2=[0.75*DJ(δδ)+ (2.807/Q0)RJ]	UI	0.180 (**0.18**)	0.319	0.329 (**0.35**)	0.441 (**0.46**)
J9=[DJ(δδ)+ (6.219/Q0)RJ]	UI	0.260 (**0.26**)	0.480	0.502 (**0.47**)	0.694 (**0.63**)
DDPWS	UI	(**0.07**)		0.103	
5E-5 (Q5 = 3.8906)	UI	0.241	0.429	0.443	0.549
TJ (Q0 = 7.034)	UI	0.267	0.497	0.523	0.729
DJ(δδ)	UI	0.210	0.344	0.344	0.426
RJ (Q0 = 7.034)	UI	0.057	0.153	0.179	0.303

Base case has been updated for D2.0 TP1 allocations. Bold entries indicate normative requirements.

The above table shows consequences if jitter allocations at TP2, TP3 and TP4 are based on a modified dual-Dirac model where only 75% of DJ(δδ) is captured in J2 measurements. For this table all other jitter contributions, from the Tx, cable plant and Rx are the same as on the prior page, i.e. all the differences are due to the differences at TP1.

As can be seen above the SRS conditions are affected. TDP limits and results would also be affected. More work is required to adequately address this issue.

Dual-Dirac Jitter Model & J2



As can be seen in the accompanying image, J2 may not be well estimated by a dual-Dirac jitter model. Depending on the method used to determine dual-Dirac DJ and/or RJ, a dual-Dirac jitter model may always over predict J2. Consequently J2 limits based on such a model would permit more jitter than expected.

From the image one can infer that J2 and J9 results are derived from a single of samples.

Min Pave, Max OMA & Peak Po determination

- For the Tx there are three primary output power attributes, Min OMA, Max Pave and Min ER. From these and a reasonable assumption of Max ER, Max OMA, Min Pave and Max Peak Po can be calculated.
- A Max ER of ~ 9.4 dB was chosen as a level unlikely to impact other acceptable transmitters. That is transmitters with ER > ~9 are not expected to have adequate transient performance for 10 GBd operation. Then:

  - Max OMA (3 dBm) is a function of Max ER (9.4 dB) and Max Pave (1 dBm)

  - Min Pave (-8 dBm) is a function of Min OMA (-3 dBm) and Max ER (9.4 dB)

  - Max Peak Po (4 dBm) is a function of Max ER (9.4 dB) and Max Pave 1 dBm) with an additional allowance for a 10% overshoot.

TDP Determination

- **Define Ref Rx: S = -14.5 dBm, BW = 7465 MHz, Rx DJ = 0, BLW = 0**
- **Define Ideal Tx: OMA = -3 dBm, ER = 3 dB, tr, tf = 1 ps, RIN=0, Wavelength = 860 nm, Spectral Width = 0.1 nm, Tx DJ = 0, TP1 TJ = 0, DCD = 0, BLW = 0**
- **Define Cable Plant: Reach = 100 m OM3, Attenuation = 0, Pmn = 0**
- **For above conditions and for Margin = 0 with TP4 TJ = 0.674 UI,
the Ref case S = -14.06 dBm (Ref Attenuation (Link Loss) = 11.06 dB)
The 0.44 dB loss of sensitivity is all ISI related.**
- **Replace Ideal Tx with Worst Case Baseline Tx and for Margin = 0 with TP4 TJ = 0.674 UI, S = -10.39 dBm (Attenuation (Link Loss) = 7.39 dB)
Sensitivity difference = 3.67 dB compared to D2.0 Max TDP = 4 dB.**
- **Replace 100 m OM3 with 2 m OM3 and filter to yield same penalties with 2 m OM3 as 100 m OM3; combined filter and Ref Rx BW = 6091 MHz.**
- **Exploration 1: Replace 100 m OM3 with 2 m OM3 and filter to yield same channel output transition times with 2 m OM3 as 100 m OM3; combined filter and Ref Rx BW = 6174 MHz.**
- **Exploration 2: Maintain 7465 MHz Ref Rx BW and adjust TDP for 0.52 dB difference in penalties between bandwidths of 6091 MHz and 7465 MHz
Max TDP = 3.4 dB.**

TDP Rx BW Sensitivities

RIN12OMA	tr, tf	TP3 DJ	WC DUT	WC DUT	WC DUT	WC DUT
			100m OM3	BW=6091	BW=6174	BW=7465
-130	35.6	0.248	3.67	3.67	3.63	3.15
-140	39.64	0.248	3.67	3.67	3.63	3.16
-126	29.15	0.248	3.67	3.67	3.62	3.11
-140	29.15	0.314	3.67	3.67	3.62	3.11
-140	35.6	0.278	3.67	3.67	3.63	3.15
-126	35.6	0.199	3.67	3.66	3.62	3.15
-126	39.64	0.158	3.67	3.67	3.62	3.17
-140	27.75	0.248	2.67	2.67	2.62	2.15
-128	21.42	0.248	2.67	2.67	2.63	2.09
-128	28.24	0.206	2.67	2.67	2.63	2.16
-140	33.60	0.206	2.67	2.67	2.63	2.19
-140	35.60	0.188	2.67	2.67	2.63	2.19
-140	38.60	0.164	2.67	2.67	2.63	2.20

The above matrix shows a comparison of TDP results for different TDP test Rx bandwidths. For this analysis, Tx attributes RIN12OMA, transitions times and DJ were varied while keeping TDP for 100 m of OM3 constant at the max value and then a 1 dB better value. The results from the Rx BW set to yield equivalent penalties were the most constant, then the results from the Rx BW picked to yield equivalent transition time, and lastly the results from the case where Rx BW remained at the Ref Rx BW. However, even the deviations of the most variable are modest.

SRS Determination

- **The SRS limit and conditions can be based on a worst case Tx, including TP1 conditions, and worst case cable plant.**
- **As usual, differences from Clause 52 experience are due to the larger eye width requirement at TP4**
- **The SRS limit (-5.4 dBm) is Min OMA (-3 dBm) at Max TDP minus the channel insertion loss (1.86 dB) and the combined noise penalties (0.53 dB). Only ½ Pcross is included.**
- **SRS jitter stress is simply the jitter, here J2 (0.343 UI) and J9 (0.457 UI), expected at TP3 for worst case conditions. In D2.0 J2 stress = 0.35 UI and J9 stress = 0.47UI**
- **VECP (1.84 dB) is the ISI penalty at 0.5 UI offset for TP3 DJ (1.45 dB + 0.14 dB) including the noise (0.25 dB) captured in the all but 0.1% VECP histogram.**

Eye Masks

- **Practical considerations, especially test time, appear to limit eye masks to ~ 1E6 samples (~40 s at 40k samples/s where 1 UI occupies 0.6 of the screen).**
- **Fortunately this is sufficient to capture high probability waveform attributes such as overshoot, ringing and other largely deterministic attributes.**
- **At TP2, since TPD captures the effects of transition times, noise and jitter, setting the x-coordinates of the TP2 mask at the jitter contours seems unnecessarily redundant and costly. It seems reasonable to back-off one to two standard deviations of RJ from the jitter contours.**
- **At TP1 there are DDPWS, J2 and 9 requirements and again, setting the x-coordinates of the TP1 mask at the jitter contours seems unnecessarily redundant and costly. While there is no TDP like requirement at TP1, adding a Qsq requirement may resolve the noise concern and permit backing off the jitter contours by one to two standard deviations of RJ.**
- **TP4 mask issues are similar to those at TP1.**

10G Ethernet Link Models

The link model (hereafter 10GbE) used in development of 10G Ethernet (10GEPBud3_1_16a.xls) is available at the IEEE P802.3ae 10Gb/s Ethernet Task Force Serial PMD documents website http://www.ieee802.org/3/ae/public/adhoc/serial_pmd/documents/ .

One of several available discussions, The 10G Ethernet Link Model, is available at the IEEE HSSG website *http://www.ieee802.org/3/hssg/public/nov06/dawe_01_1106.pdf* . This presentation includes an extensive list of references.

Extensions for the 10GbE model that include effects of source RJ at TP1 and DJ added between TP3.5 and TP4, calculates the open eye width at TP4, providing a means to harmonized power penalties and jitter are described in petrilla_02_1108. Using the extended model to generate Tx eye masks is described in petrilla_03_1108.

10GbE Link Model - Assumptions

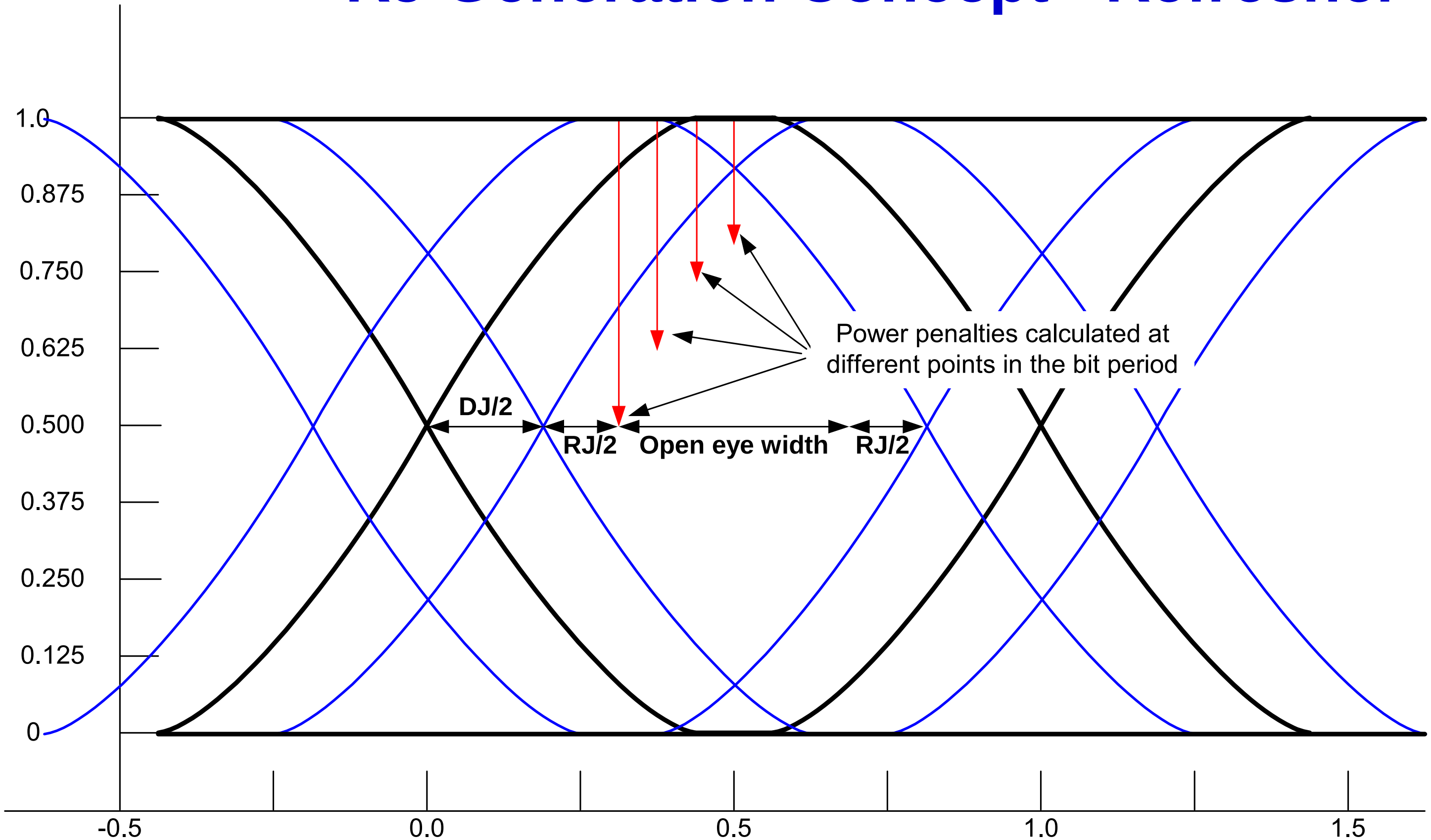
- Transmitters have a Gaussian impulse response with a similar step response for rising and falling edges.
- Fibers have a Gaussian impulse response.
- Receivers have a non-equalized, raised-cosine response.
- The reference (or test) receiver has a 4-th order Bessel-Thomson (BT) response at 75% of the signal rate.
- Modal noise introduced by partial optical mode coupling in the cable plant is limited to a noise penalty, Pmn, of 0.3 dB by limiting the maximum connector loss to 1.5 dB.
- RIN is white over the frequency range of interest.

Additional Assumptions for Extension

- Jitter at the interfaces can be partitioned into random, RJ, and deterministic, DJ, components using Dual Dirac jitter methods. For the rest of this presentation, DJ refers to Dual Dirac DJ.
- The signal (amplitude) noise in the optical link is transformed into random (Gaussian) jitter by the non-vertical edges of the signal transitions.
- Input referred receiver noise is Gaussian.
- At the corners of the eye opening, the vertical closure due to the power penalties and signal loss coincides with the horizontal closure due to jitter.
- Receiver sensitivity includes the minimum output swing requirements for the receiver.

Extended 10GbE Link Model

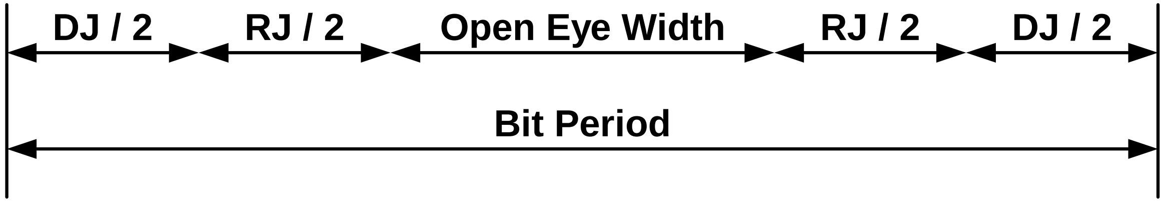
RJ Generation Concept - Refresher



- Above, power penalties are calculated, using relationships in the 10GbE model, moving away from the center of the eye until the power penalties equal the signal magnitude. This defines the end point of the open eye for a 10^{-12} BER contour.
- For total penalties, Pt(ew/2), and displacement from the center of the eye, ew/2, find ew/2 where Pt(ew/2) = Power Budget – (Connector Loss +Pattenuation).

Extended 10GbE Link Model

Accounting at TP3.5



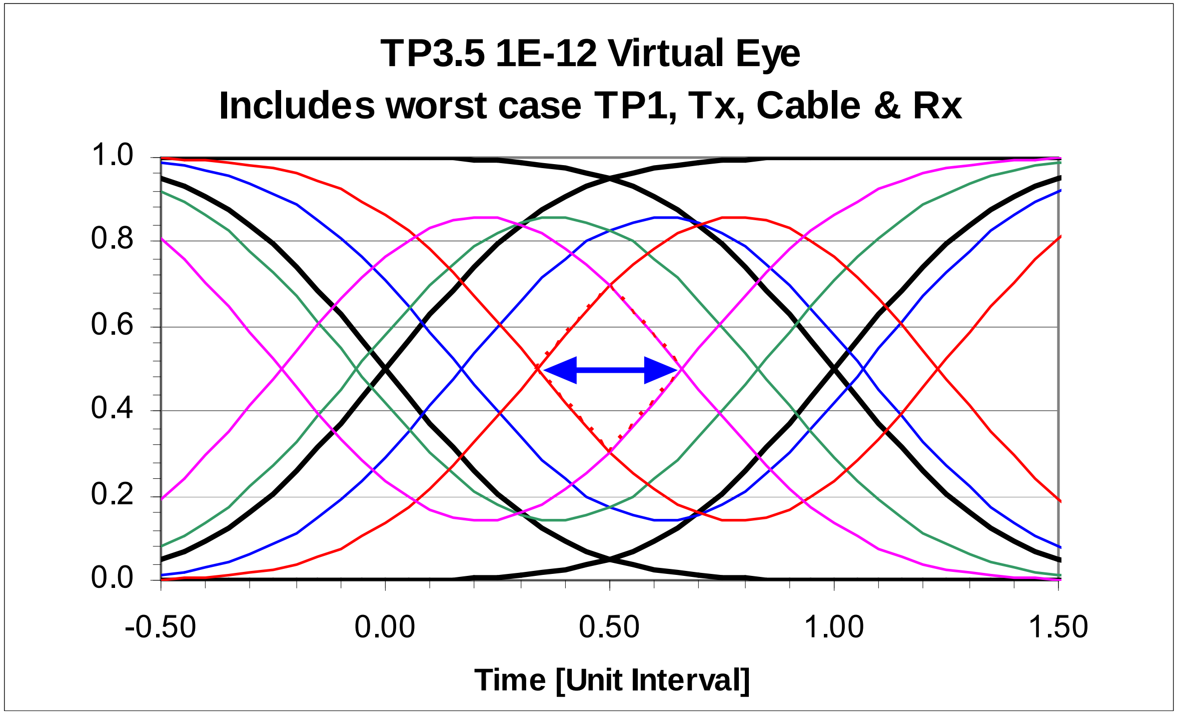
- Unit bit period = 1 = TJ + Eye-width = DJ + RJ + Eye-width.
- The bit period comprises only three terms. What isn't DJ or open eye-width is RJ. Since DJ, including DCD, is allocated, it is known. Then, all that is needed is to determine eye-width or RJ.
- The 10GbE model determines power penalties for the fiber optic channel from TP1 to TP3.5 but doesn't include the RJ present at TP1, RJ_{TP1}, and DJ, DJ_{Rx}, generated between TP3 and TP4. Consequently, first RJ generated between TP1 and TP3.5, RJ_{ch}, will be determined from the associated power penalties and then combined with RJ_{TP1} to yield RJ_{total}. Then TJ, TJ_{TP4}, and the eye width at TP4 will be determined as follows.
- $RJ_{total} = RJ_{TP4} = Sqrt(RJ_{ch}^2 + RJ_{TP1}^2)$
- $TJ_{TP4} = DJ_{TP3} + DJ_{Rx} + RJ_{total}$
- $\text{Eye-width}_{TP4} = 1 – TJ_{TP4}$

Tx Eye Mask
Generation - Overview

- The following pages present a method of generating eye masks based on BER contours, i.e.
  - show 10^-12 BER contours
  - show progression of required contour/eye from TP3.5 to TP2
  - show translation of contour into mask
  - show translation of contours and masks from a BER = 1E-12 basis to a 5E-5 hit ratio basis.

  <u>Contour/Mask Generation Approach and/or Assumptions:</u>
  - For contours each bit is at worst case dual-Dirac deterministic jitter, DJ(δδ).
  - Receiver requirements are based on unstressed receiver sensitivity.
  - The Reference/Test Rx only contributes RJ and ISI generated DJ.
  - In test set-ups, observed optical-noise and random jitter beyond that due to TP1 jitter, RIN of the device under test, test receiver sensitivity or test equipment timing uncertainty, is due to modal noise associated with incomplete modal coupling at the optical connectors.
  - Although the Reference/Test Rx assumes a 4^{th}-Order BT response, no adjustment is made to the receiver time constant parameter in the spreadsheet.

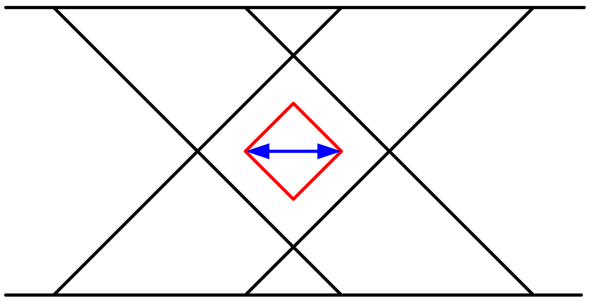
Tx Eye Mask - Generation at TP3.5



- The above figure shows eye contours generated at TP3.5, i.e. decision point for defined worst case link conditions. All Rx DJ(δδ) allocation is also included. Impairments from the observing test equipment are not included. Note approximate diamond shape.
- The contours are generated as if every bit is at the maximum DJ(δδ). For PRBS patterns only 25% of the bits are isolated center bits in …010… or …101… patterns. Consequently, the contours are conservative.
- In the eye contour for TP3.5 recall that since the decision point in the receiver is followed by a high gain comparator and/or the Rx minimum output swing is included in the sensitivity test, BER requirements are satisfied even if the diamond is collapsed to the blue line. The required length of the blue is given by the eye opening required at TP3.5 plus any Rx contributed DJ(δδ) generated after the decision point.

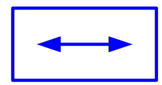
Tx Eye Mask – Simplified Rx Based Requirement

Generation – Progression (1)

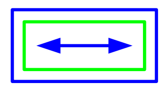


- Here the above figure shows a simplified eye contour for TP3.5. Again, the BER requirement is satisfied by the blue line. On the right a progression is shown beginning with the eye contour required at TP3.5 and working upstream to the output of the transmitter. For brevity only eye height adjustments are discussed. Adjustments are, however, also required for eye width. The combined effect may produce rounded or semi-ellipsoidal ends.

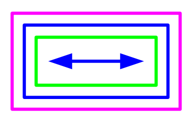
- 10^-12 eye contour needed at TP3.5



- Eye contour for a virtual TP3 adjusted for worst case Rx sensitivity. Eye Height = Rx sensitivity.



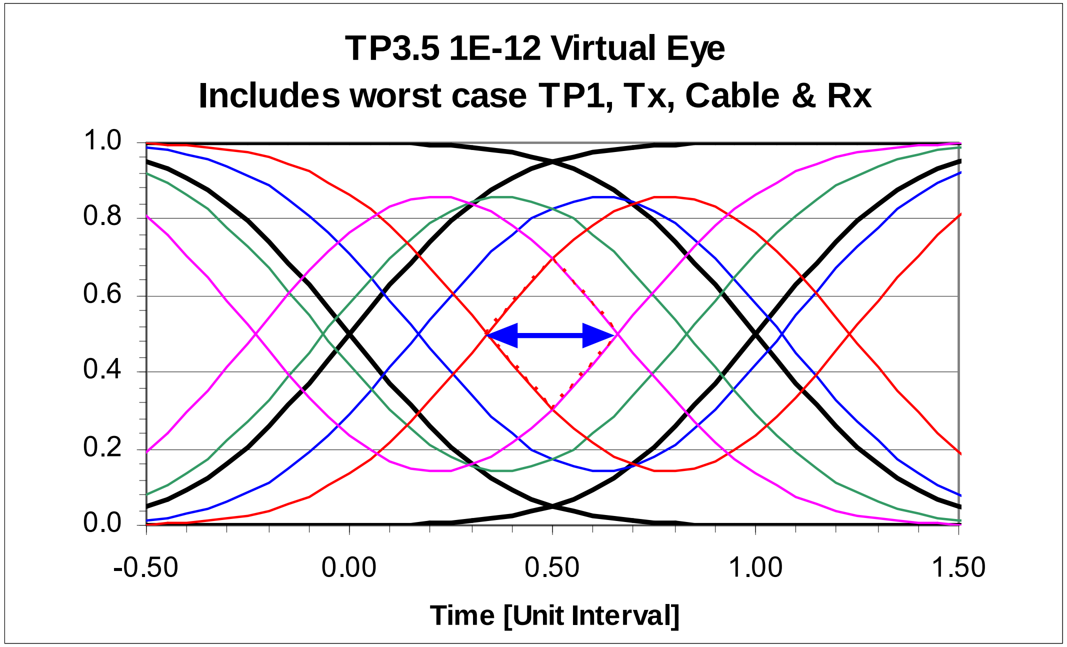
- Eye contour for an observed TP3 adjusted for worst case Rx sensitivity and difference between the worst case receiver and the test equipment receiver.

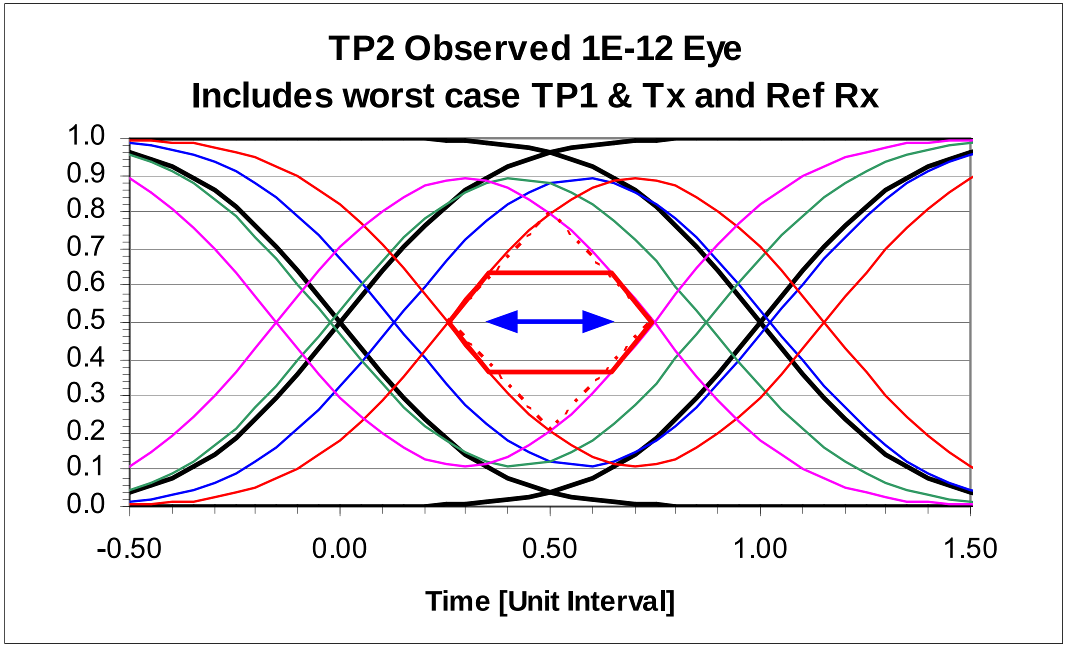


- Eye contour for an observed TP2 adjusted for worst case Rx sensitivity and difference between the worst case receiver and the test equipment receiver and further adjusted for channel losses and penalties.

Tx Eye Mask
Generation – Progression (2)

Repeating the previous page, an eye mask can be based on the input signal requirements of the Rx. Here the height is based on the unstressed sensitivity and link penalties and the ends are based on the simplified diamond-shaped eye contour yielding a six-sided polygon.





Tx Eye Mask
Generation Lower Q Contours

Contours for hit ratios higher than 1E-12 can be used to define equivalent but less time consuming measurements. Here, for comparison with BER = 1E-12 contours, contours are also plotted for a test based on a hit ratio = 5E-5 .

Rejecting on a larger number of hits should reduce the variability of the margin result. Note that the contour represents a mean position for which there's a confidence interval and associated measurement variability. It's expected that the width of the confidence interval and associated measurement variability is inversely related to the square root of the reject value.