Optical Link Model for PAM-4 Multimode Channels with equalizers

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IEEE P802.3cm 400 Gb/s over Multimode Fiber Task Force
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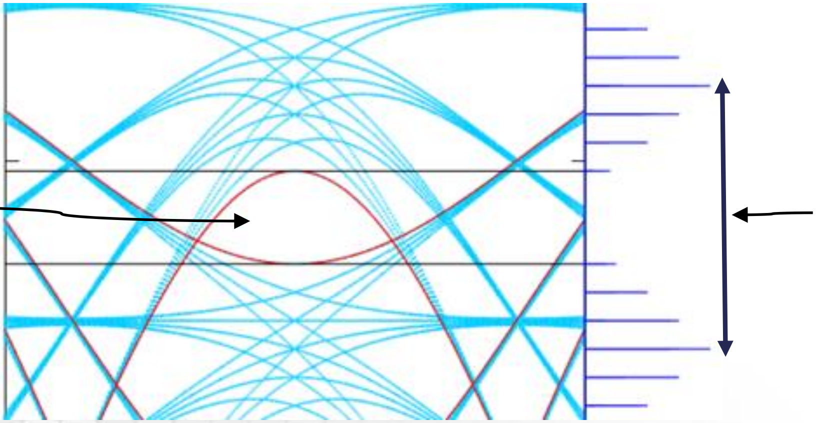
Introduction and Objectives

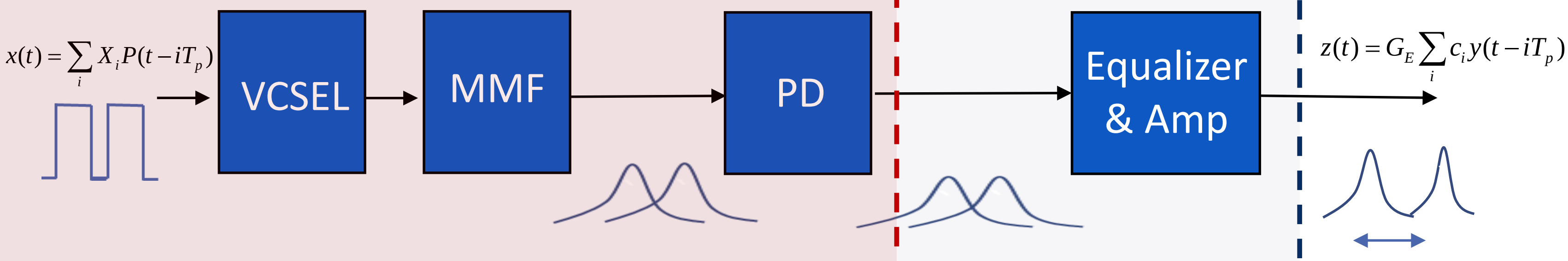
- Provide a link model tool to estimate reasonable worst-case channel reaches for multimode fiber links using VCSEL based transceivers and PAM-4 modulation
    - 50GBASE-SR, 100GBASE-SR2, 200GBASE-SR4, 400GBASE-SR8, 400GBASE-SR4.2, BiDi and others operating in the spectral window 840-953nm
- Previous link models compute penalties based on worst-case eye opening
    - Too pessimistic for equalized PAM-4 links
        - The statistical eye amplitude method (castro_3cm_01_0518) provides a fast and accurate estimation.
- This presentation describes the eye amplitude estimation method of all the penalties (ISI and noise penalties) in the link model.
- An implementation of the statistical eye amplitude link model in Matlab will be shown during the presentation.

Current approach "Worst-Case eye opening"



Proposed "**statistical eye amplitude"** method: the information from the eye amplitude PDF is included in the evaluation to provide a reasonable worst-case link

Equalized Link model



$$h_e(t)=0.5[\mathrm{erf}(k\frac{[2t+T_p]}{T_C})+\mathrm{erf}(k\frac{[-2t+T_p]}{T_C})]$$

$$h_f(t)=\sum_{i=-2}^{2} c_i h_e(t-iT_p)$$

Implementation

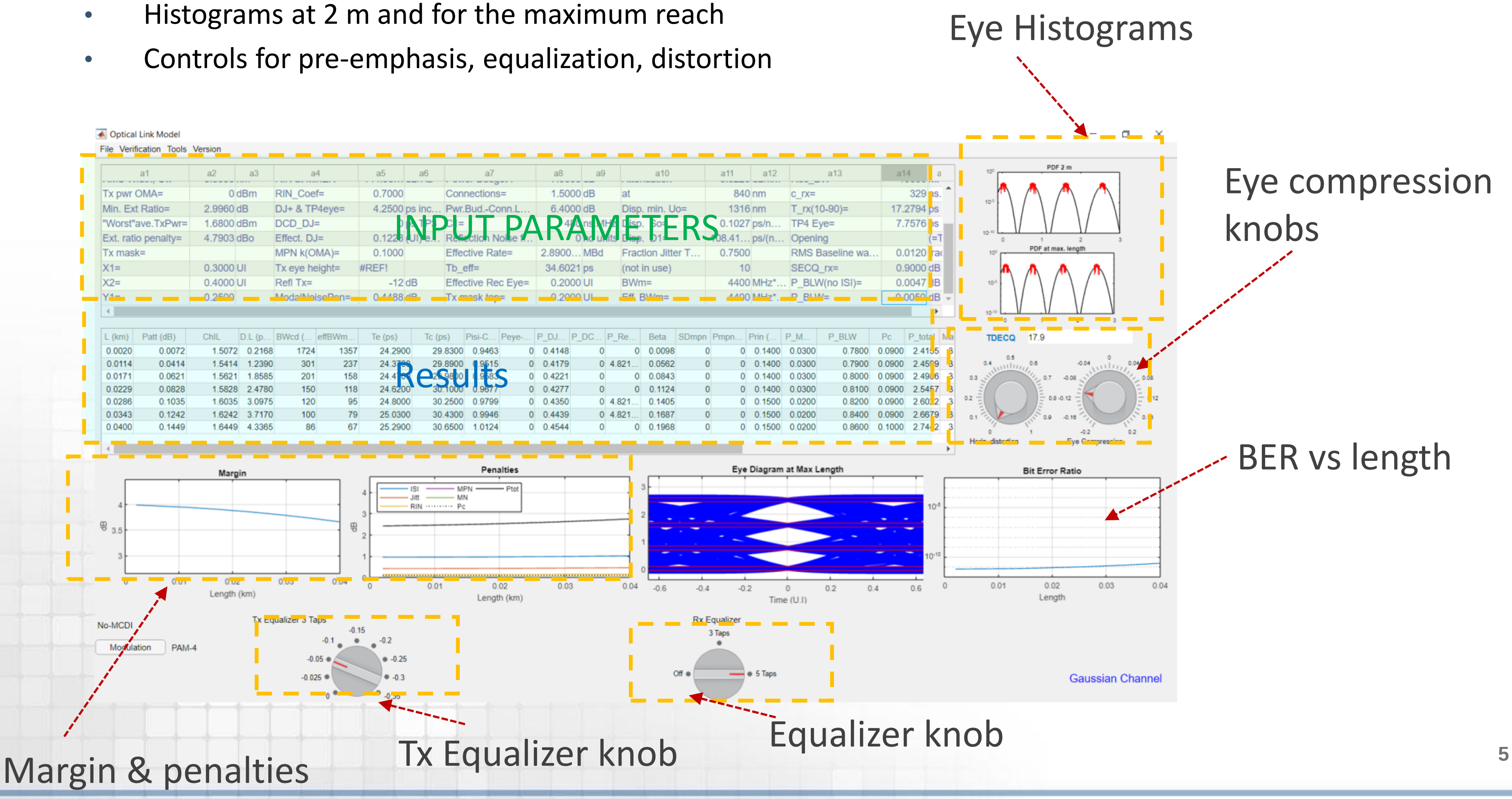
- Evaluated several options shown in Table.

Platform	Speed	Required License	Complexity	Size
Excel ®	Very Slow	MS Office	Very High	Very small
Excel ® with Visual Basic Application (VBA)	Slow	MS Office	Medium	Very small
Excel ® with Dynamic time libraries	Fast	MS Office	High	Small
MATLAB ® compiled	**Fast**	**None**	**Medium**	**Large 500 Mbytes min**

- Excel with simple VBA could be good for worst case eye closure but not for eye amplitude method.
- Latest version, presented here implemented in MATLAB (compiled)

Implementation

- Spreadsheet approach
  - Top menu for basic functions (save load,…)
  - Section for input parameters
  - Section for results
  - Eye diagram (ISI-Jitter penalties)
  - Histograms at 2 m and for the maximum reach
  - Controls for pre-emphasis, equalization, distortion



Implementation

- Computation of link penalties for PAM-2 and PAM-4
- Transmitter equalizer only 3 taps (symmetric) with fixed options
- Receiver equalizer MMSE 3 or 5 Taps
  - Histograms computed at the center of the eye for 2 m and maximum reach
  - Show the histograms due to ISI-Jitter component (red trace) and also the noise components
  - Noise enhancement due equalizer included
- Eye compression knob only allow the range of values shown in dial
- Eye diagram (ISI-Jitter penalties only)
- Receiver equalizer MMSE 3 or 5 Taps
  - Noise enhancement due equalizer included

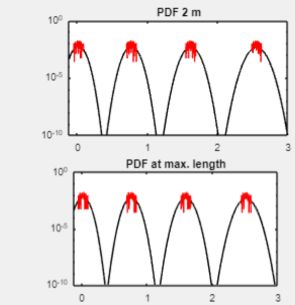
Implementation

- Real time demo shown during the presentation

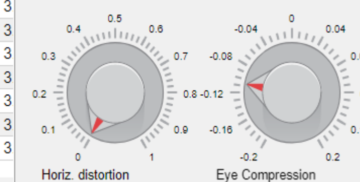
File Verification Tools Version

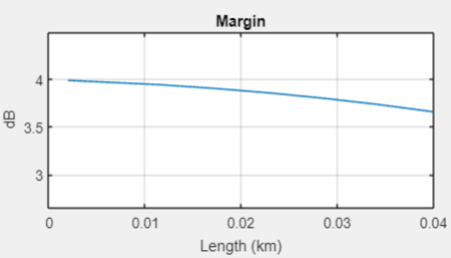
a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12	a13	a14	a
Tx pwr OMA=	0	dBm	RIN_Coef=	0.7000		Connections=	1.5000	dB	at	840	nm	c_rx=	329	ns.
Min. Ext Ratio=	2.9960	dB	DJ+ & TP4eye=	4.2500	ps inc…	Pwr.Bud.-Conn.L…	6.4000	dB	Disp. min. Uo=	1316	nm	T_rx(10-90)=	17.2794	ps
"Worst"ave.TxPwr=	1.6800	dBm	DCD_DJ=	0	ps TP3	C1=	480	ns.MHz	Disp. So=	0.1027	ps/n…	TP4 Eye=	7.7576	ps
Ext. ratio penalty=	4.7903	dBo	Effect. DJ=	0.1228	(UI) e…	Reflection Noise f…	0	no units	Disp. D1=	-108.41…	ps/(n…	Opening		(=T
Tx mask=			MPN k(OMA)=	0.1000		Effective Rate=	2.8900…	MBd	Fraction Jitter T…	0.7500		RMS Baseline wa…	0.0120	frac
X1=	0.3000	UI	Tx eye height=	#REF!		Tb_eff=	34.6021	ps	(not in use)	10		SECQ_rx=	0.9000	dB
X2=	0.4000	UI	Refl Tx=	-12	dB	Effective Rec Eye=	0.2000	UI	BWm=	4400	MHz*…	P_BLW(no ISI)=	0.0047	dB
Y1=	0.2500		ModalNoisePen=	0.4488	dB	Tx mask top=	0.2000	UI	Eff. BWm=	4400	MHz*…	P_BLW=	0.0050	dB

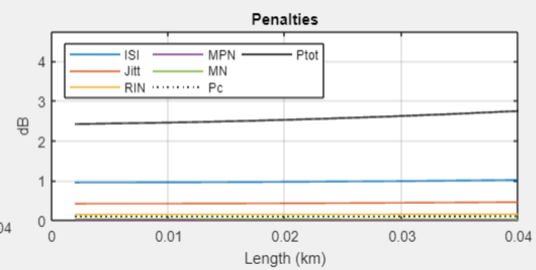
L (km)	Patt (dB)	ChIL	D.L (p…	BWcd (…	effBWm…	Te (ps)	Tc (ps)	Pisi-C…	Peye-…	P_DJ…	P_DC…	P_Re…	Beta	SDmpn	Pmpn…	Prin (…	P_M…	P_BLW	Pc	P_total	Ma
0.0020	0.0072	1.5072	0.2168	1724	1357	24.2900	29.8300	0.9463	0	0.4148	0	0	0.0098	0	0	0.1400	0.0300	0.7800	0.0900	2.4155	3
0.0114	0.0414	1.5414	1.2390	301	237	24.3700	29.8900	0.9515	0	0.4179	0	4.821…	0.0562	0	0	0.1400	0.0300	0.7900	0.0900	2.4599	3
0.0171	0.0621	1.5621	1.8585	201	158	24.4700	29.9800	0.9583	0	0.4221	0	0	0.0843	0	0	0.1400	0.0300	0.8000	0.0900	2.4986	3
0.0229	0.0828	1.5828	2.4780	150	118	24.6200	30.1000	0.9677	0	0.4277	0	0	0.1124	0	0	0.1400	0.0300	0.8100	0.0900	2.5457	3
0.0286	0.1035	1.6035	3.0975	120	95	24.8000	30.2500	0.9799	0	0.4350	0	4.821…	0.1405	0	0	0.1500	0.0200	0.8200	0.0900	2.6022	3
0.0343	0.1242	1.6242	3.7170	100	79	25.0300	30.4300	0.9946	0	0.4439	0	4.821…	0.1687	0	0	0.1500	0.0200	0.8400	0.0900	2.6679	3
0.0400	0.1449	1.6449	4.3365	86	67	25.2900	30.6500	1.0124	0	0.4544	0	0	0.1968	0	0	0.1500	0.0200	0.8600	0.1000	2.7442	3

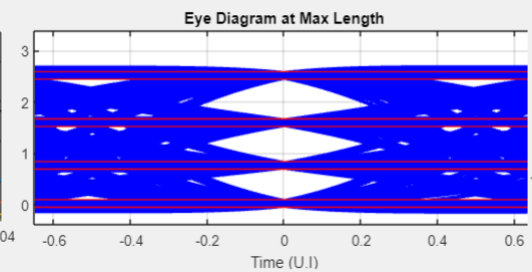


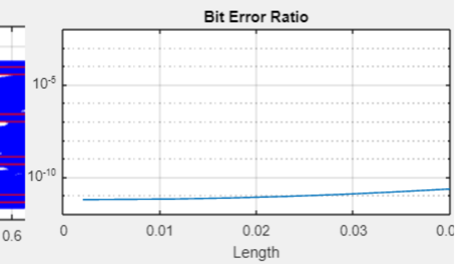
TDECQ 17.9





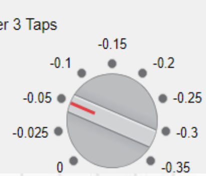


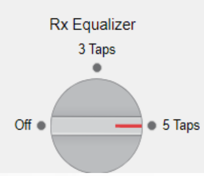




No-MCDI

Modulation PAM-4





Gaussian Channel

Summary & Conclusions

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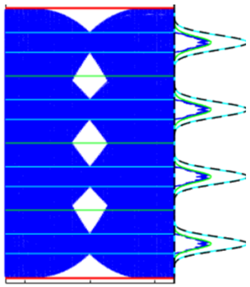
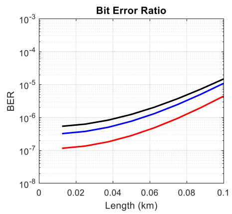
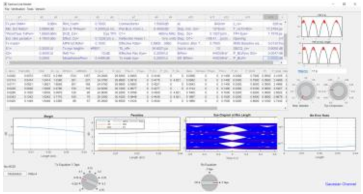
- We described Panduit's link model for PAM-4 signals over multimode fiber
  - Statistical eye amplitude method
- A general description of the functionalities and a demonstration shown during the presentation
  - Plot of histograms, eye diagrams and BER
  - Tested response time for any change in input parameters
- Model details of the model included in annexes:
  - Fast & accurate method to compute the eye diagram histograms
  - Signal dependent noise treatment
  - Computation Method for Margin and Penalties
- The model was implemented in Matlab GUI (compiled)
  - GUI implemented
  - Compiles, (no license required by user)
  - Modular
    - Penalties (currently being reviewed such as MN) could be updated
  - Could be available in IEEE website if solicited.







References

PANDUIT

- Previous work for 1Gbps and 10Gbps using NRZ link models
  - Del Hanson, David Cunningham, Piers Dawe and David Dolfi (for 10G)
- Prior works for equalized channels :
  - D. Cunningham proposed a 3-tap equalizer for PI-6 (12-044v1, 12-123v0)
    - However, required several sheets (one per link length) and valid only for NRZ
  - PAM-4 power budget penalties require more sophisticated equations than NRZ
  - Equalization taps need to be efficiently computed for each length in one sheet
- In Fibre Channel, PAM-4 has been modeled using additional software packages
  - For Python languages 16-013 v0, 16-012v0 (Richard Johnson)
  - For Matlab 15-263v0
  - An Excel VBA was proposed in T11-2016-065v0
    - Fully implemented PI-6P (32GFC NRZ)
- Investigation of 60 Gb/s 4-PAM Using an 850 nm VCSEL and Multimode Fiber
  - Journal of Lightwave Tech. Vol 34 (16) , April 2016
- Optical Link Model for PAM-4
  - castro_3cm_01_0518

Backup

Annex I
Direct Method to compute the Eye PDF from the input (ideal) PDFs and from the channel response

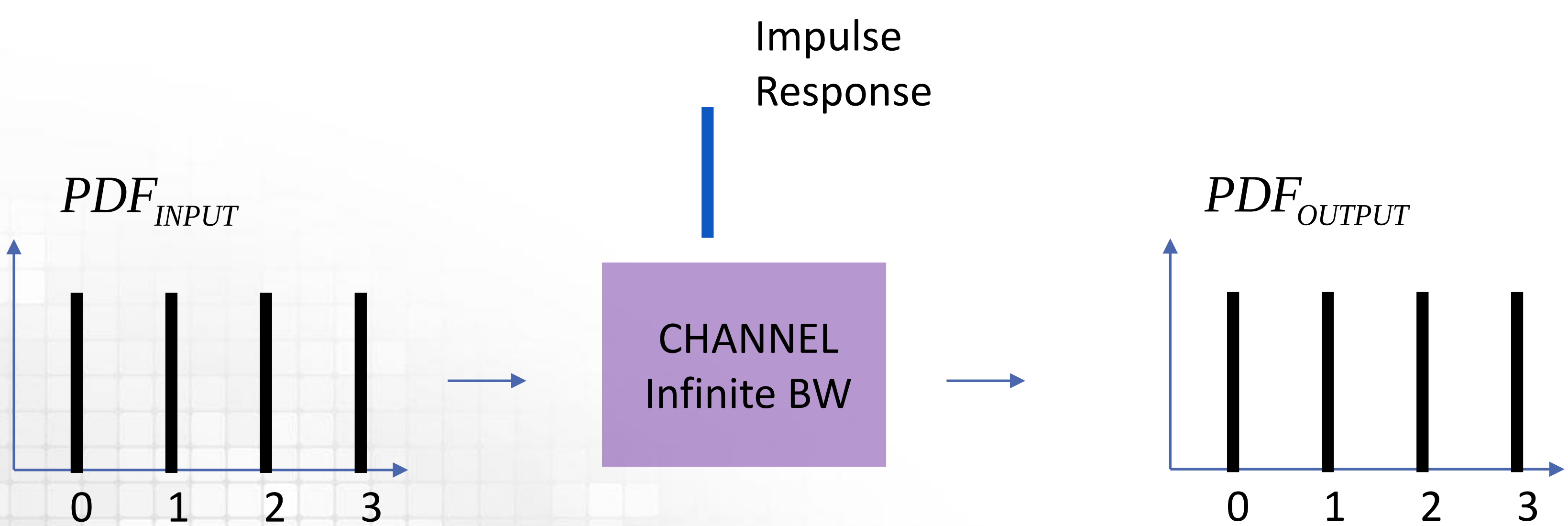
Description

- The method shown in this annex provides an very accurate and fast computation of the eye diagram amplitude histogram.
  - It only needs the input distribution, i.e. for PAM-4 4 delta functions with 25% probability each, and the impulse response of the channel.
- It can include the deterministic jitter of the channel

- The proposed method provides a general solution that does not need the simulation of the channel (sending billion of symbols) . Therefore, is significantly faster and used in some parts of the presented link models.
- Examples, and more details of the operation in shown in next slides.

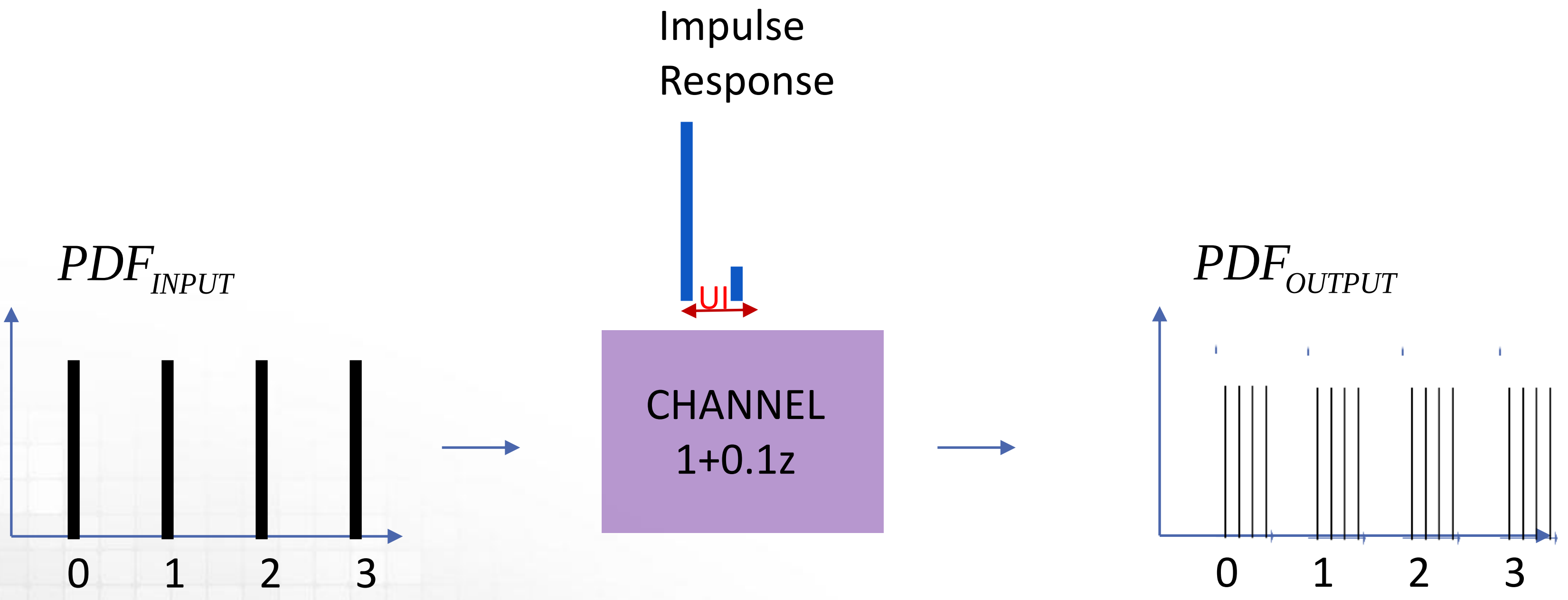
Eye Diagram Statistics

- For a time-invariant channel the PDF of the eye at a specific sampling time can be obtained using the statistical properties of the transmitted data (PDF) and the impulse response of the channel.
  - The resultant PDF using this method is equivalent of sending a pseudo random sequence of "infinite length"
- A very simple example to illustrate this method is shown in the following 3 steps
  1. *A PAM-4 signal in a channel with infinite bandwidth*



Eye Diagram Statistics

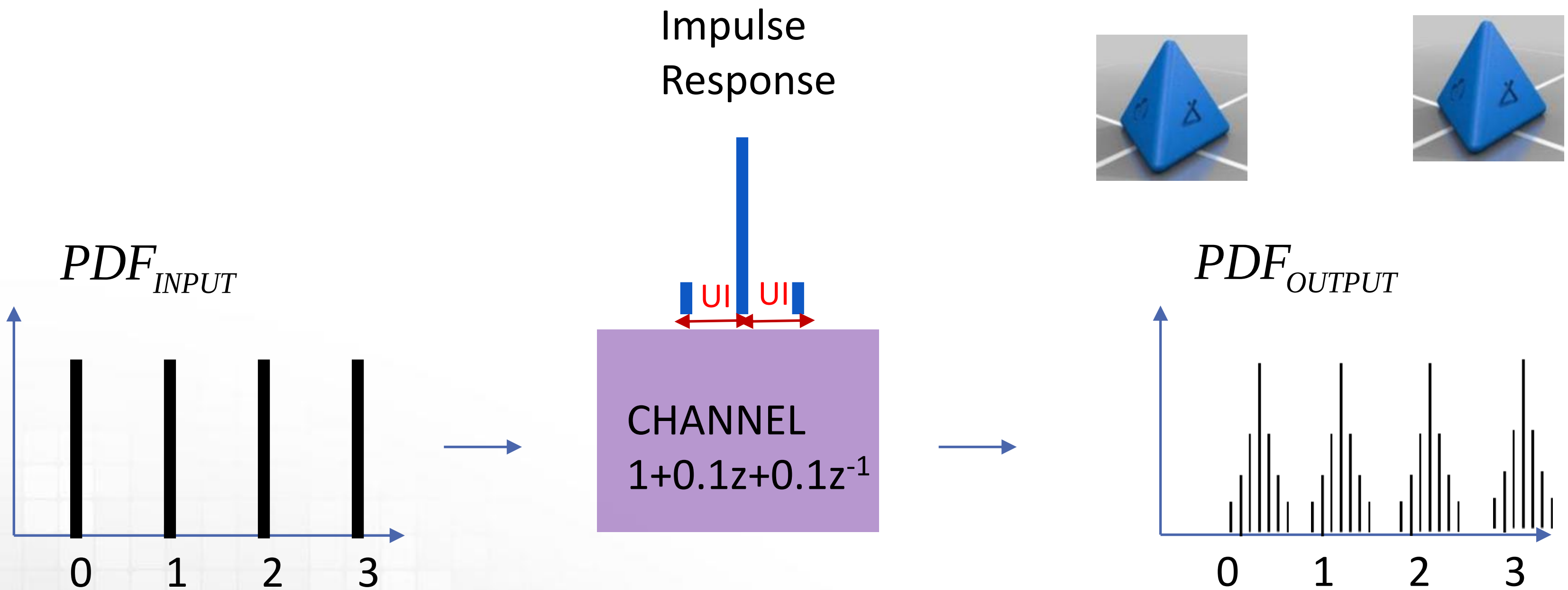
1. *A PAM-4 signal in a channel with infinite bandwidth (previous slide)*
2. *A PAM-4 signal with a channel with response 1+0.1z*



The input PFD is modified by the adjacent pulse that add 0, 0.1, 0.2 or 0.3 each 25% of the time.

Eye Diagram Statistics

- A very simple example to illustrate the method is shown
  1. *A PAM-4 signal in a channel with infinite bandwidth*
  2. *A PAM-4 signal with a channel with response 1+0.1z*
  3. *A PAM-4 signal with a channel with response $1+0.1(z+z^{-1})$*



- The input PFD is modified by the adjacent pulse to the left that adds 0, 0.1, 0.2 or 0.3 each 25% of the time and by the adjacent pulse to the right that adds 0, 0.1, 0.2 or 0.3 each 25% of the time.
- What is the final PDF?
  - The modification to the PDF can be obtained by convolving the effects from the left and right side. In some way, equivalent to launching two four-sided dies (tetrahedral die) each face marked with 0,0.1,0.2,0.3.

Eye Diagram Statistics

- ***The received optical signal is given by,***

$$y(kT_p) = Y_k = \sum_i X_i h_e([k-i]T_p + J\,T_p) = h_0 X_k + \sum_{i>k} X_i h_{i-k} + \sum_{i<k} X_i h_{-(k-i)}$$

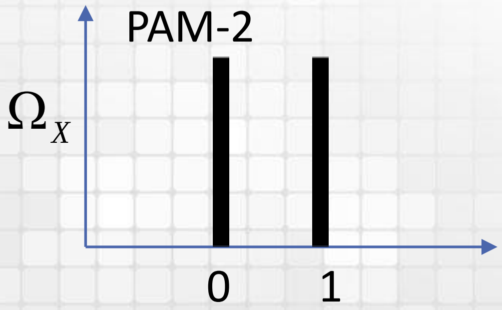
where J is the effective jitter

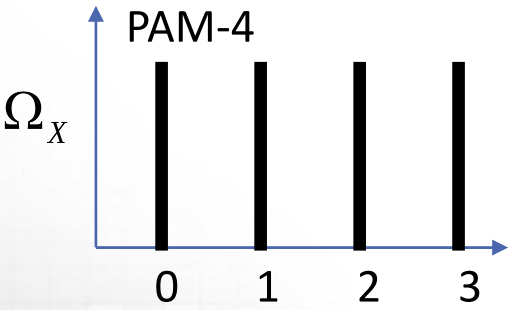
- ***The Probability Density function (PDF) of Y can be obtained using***

$$PDF_{OUTPUT}(Y_k) = PDF(h_0 X_k + \sum_{i>k} X_i h_{i-k} + \sum_{i<k} X_i h_{k-i})$$

- ***We can define the PDF of X as:*** $\Omega_X = PDF_{INPUT}(X)$

- ***Assuming, equiprobable symbols, the PDF for PAM-2 and PAM-4 are shown below,***

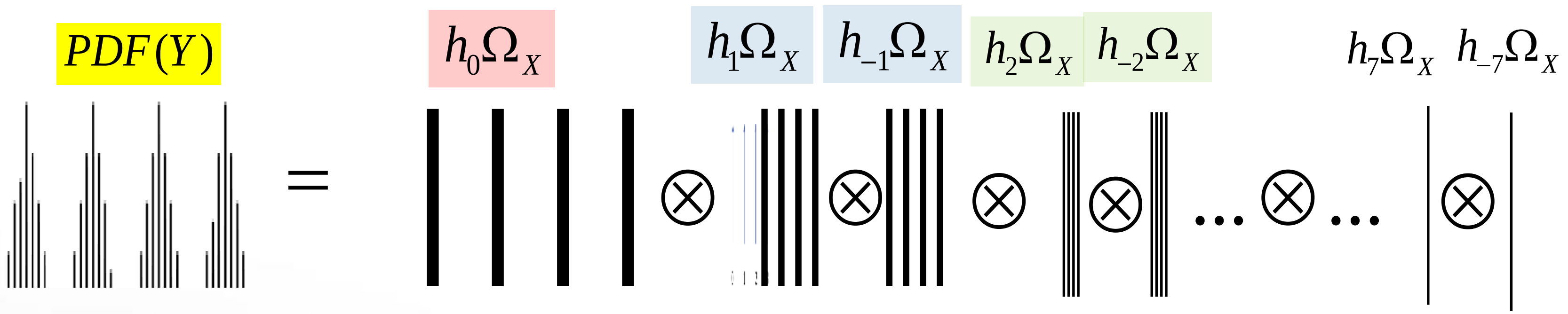




Eye Diagram Statistics: General method

- **The PDF of y can be obtained using:**

$$PDF_{OUTPUT}(Y) = h_0\Omega_X \otimes h_1\Omega_X \otimes h_{-1}\Omega_X \otimes h_2\Omega_X \otimes h_{-2}\Omega_X \otimes h_3\Omega_X \otimes h_{-3}\Omega \otimes \ldots \otimes h_7\Omega_X \otimes h_{-7}\Omega_X$$



Where $\otimes$ represents the convolution operator

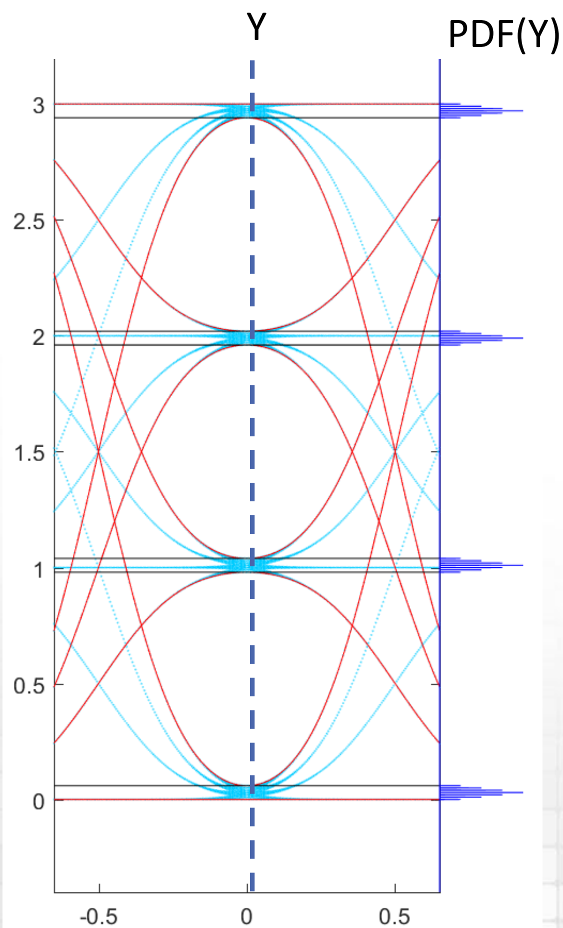
$$\Omega_X = PDF_{INPUT}(X)$$

and h_o, h_1, h_{-1}, h_2, h_{-2},… represents the impulse response of the channel sampled using the symbol period.

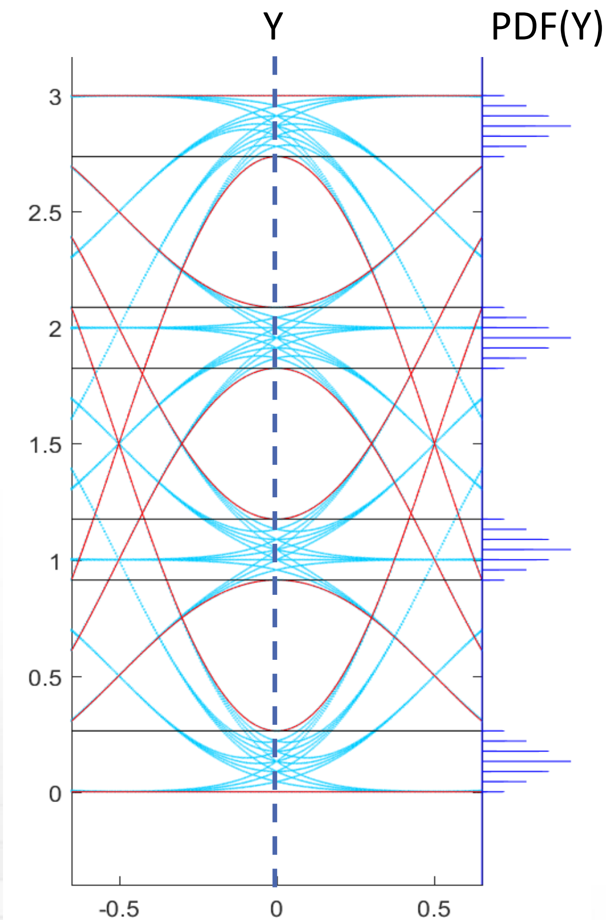
- *The exact PDF of the eye diagram at a specific sampling time can be obtained without the need of sending a pseudorandom sequence, we just need to convolve scaled versions of the input signal PDF.*
- *The scaling factor is the value of the impulse response at T, ±T, ±2T*
- *This method works also when dual-Dirac jitter is present.*

Examples Eye Diagram Statistics: No Jitter

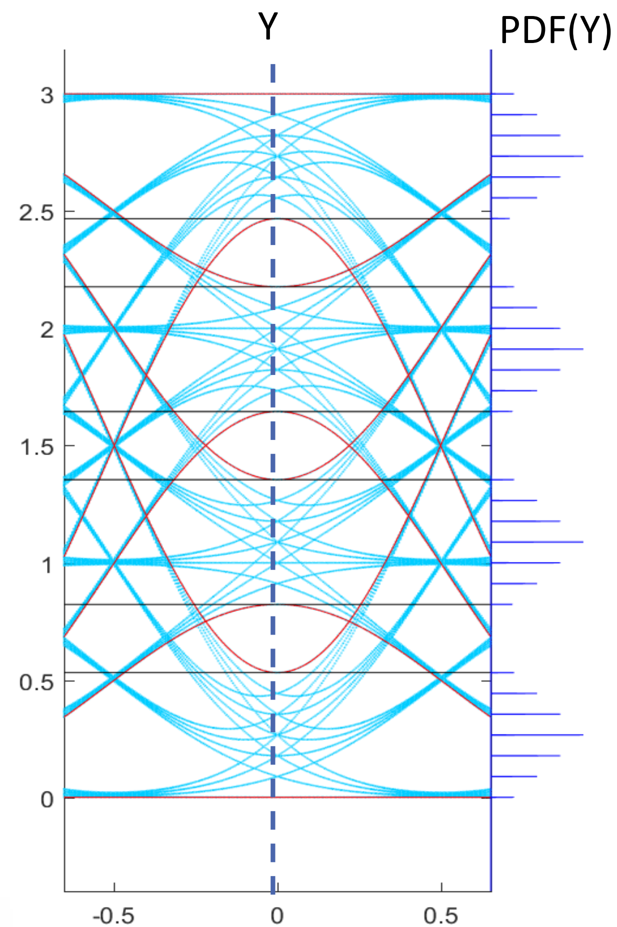
- **Using this method the PDFs for the received signal at the decision time can be computed as shown in the examples below.**



Tr/Tp=0.55



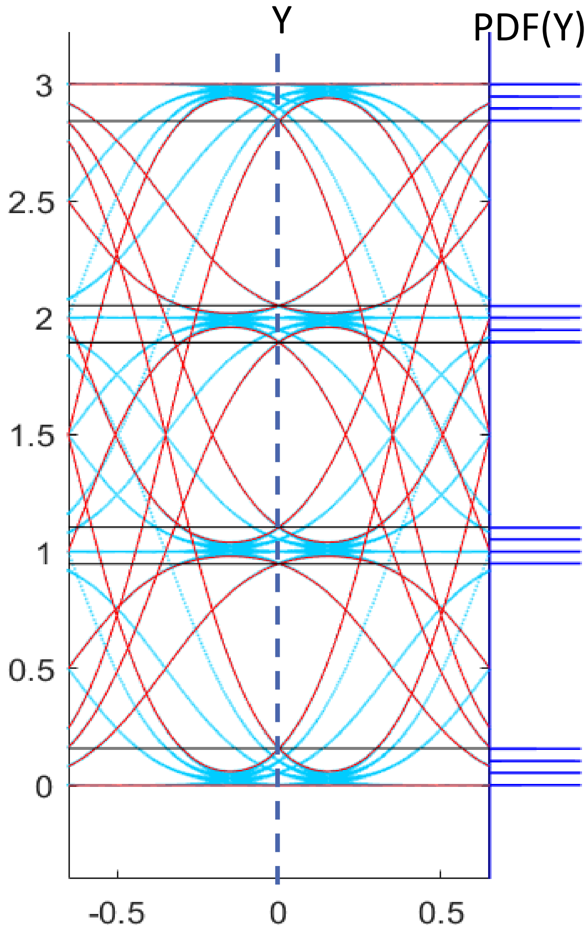
Tr/Tp=0.75



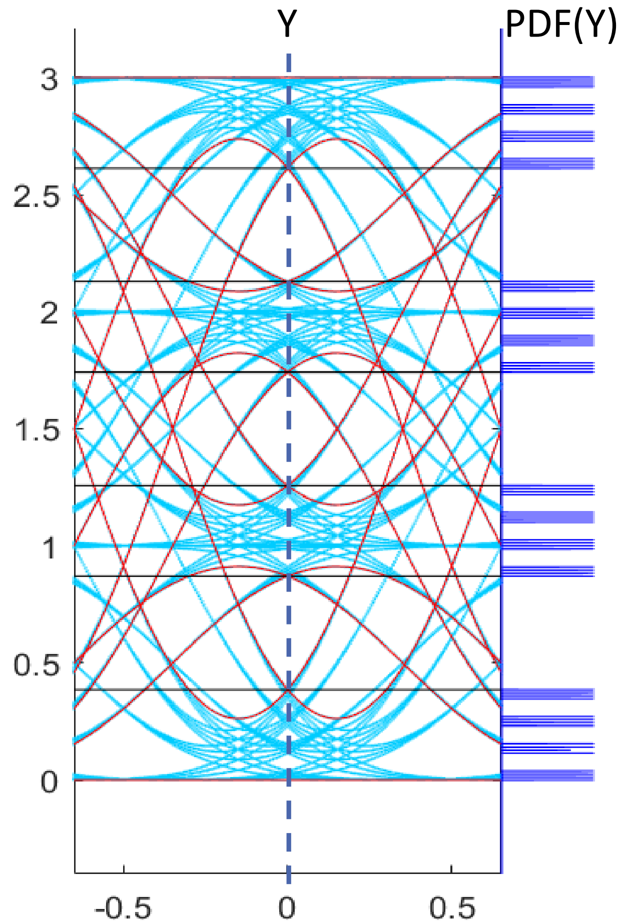
Tr/Tp=0.95

Example Eye Diagram Statistics: dual-Dirac Jitter

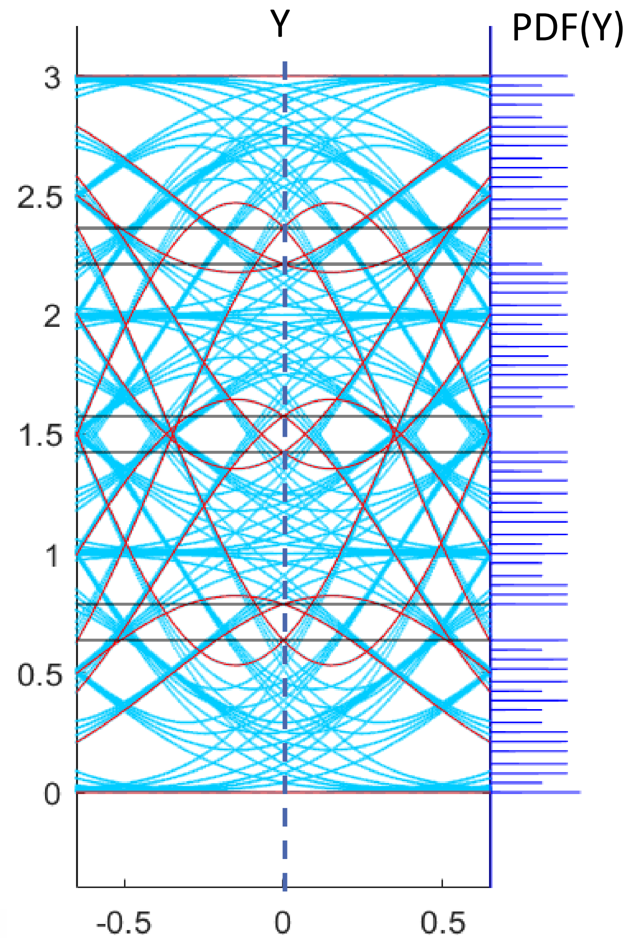
- **Using this method the PDFs for the received signal at the decision time can be computed as shown in the examples below.**



Tr/Tp=0.55, effect. J=0.3



Tr/Tp=0.75, effect. J=0.3



Tr/Tp=0.95, effect. J=0.3

Annex II
Treatment of signal dependent noises example for RIN

Example of signal dependent noises RIN_{OMA}

- IEEE 802.3ae (clause 52.9.6) defines RIN_{OMA} as the ratio of the electrically noise power normalized to a 1 Hz bandwidth and the electrical power of a square wave modulation
- The RIN_{OMA} (outer) can be measured using a scope and a square wave pattern (i.e., 8 zeros and 8 threes as indicated in 802.3bs Table 139-9). The equations to relate the measured RIN parameters to our PAM-4 equalized optical link will be shown in this section.
  - The normalized variance due to RIN can be obtained using

$$\sigma_{RIN-OMA}{}^{2} = \frac{n_0{}^2 + n_3{}^2}{2(\Delta/2)^2 \rho_{ISI-J}{}^2} = \frac{\mathrm{K}_{RIN} 10^{-RIN/10} 10^6}{\sqrt{0.477/BW_{RX}{}^2)}} \qquad \text{(D.1)}$$

  - Where 3Δ is the optical modulation amplitude without any dispersion penalties, $\mathrm{K}_{\mathrm{RIN}} = 0.7$, BW_{Rx} is the bandwidth of the receiver, and $\rho_{Te} = A_i(JT_p)$ is the reduction in the optical signal attributed only to fiber and laser (T_e).

RIN_{OMA} without eye compression

- **The RIN variances (no-normalized) for each signal level is derived**

$$n_0^{\,2} = \rho_{ISI-J}^{\;\;2}\frac{2(\Delta/2)^2}{1+ER^2}\sigma_{RIN-OMA}^{\;\;2} = (\frac{\Delta}{2}\sigma_0)^2 \qquad \text{(A.1)}$$

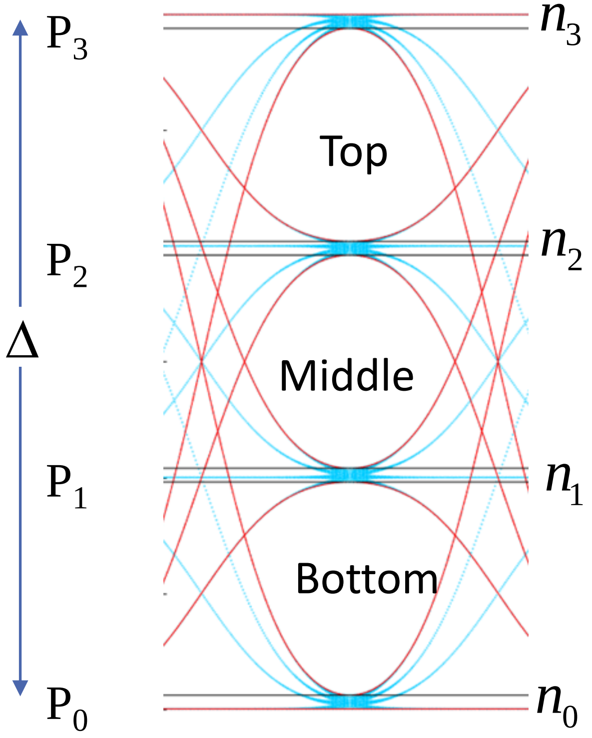
$$n_1^{\,2} = \rho_{ISI-J}^{\;\;2}2(\Delta/2)^2\frac{(ER+2)^2}{9(1+ER^2)}\sigma_{RIN-OMA}^{\;\;2} = (\frac{\Delta}{2}\sigma_1)^2 \qquad \text{(A.2)}$$

$$n_2^{\,2} = \rho_{ISI-J}^{\;\;2}2(\Delta/2)^2\frac{(2ER+1)^2}{9(1+ER^2)}\sigma_{RIN-OMA}^{\;\;2} = (\frac{\Delta}{2}\sigma_2)^2 \qquad \text{(A.3)}$$

$$n_3^{\,2} = \rho_{ISI-J}^{\;\;2}\frac{2(\Delta/2)^2}{1+ER^2}ER^2\sigma_{RIN-OMA}^{\;\;2} = (\frac{\Delta}{2}\sigma_3)^2 \qquad \text{(A.4)}$$

$$\Delta = OMA_{Tx\_outer\_linear}10^{-Losses/10} \qquad \text{(A.5)}$$

$$Losses = Connector\_Losses + Att\ Length \qquad \text{(A.6)}$$



Annex III
Computation Method for Margin and Penalties

Computation of Margin & Penalties PAM-2

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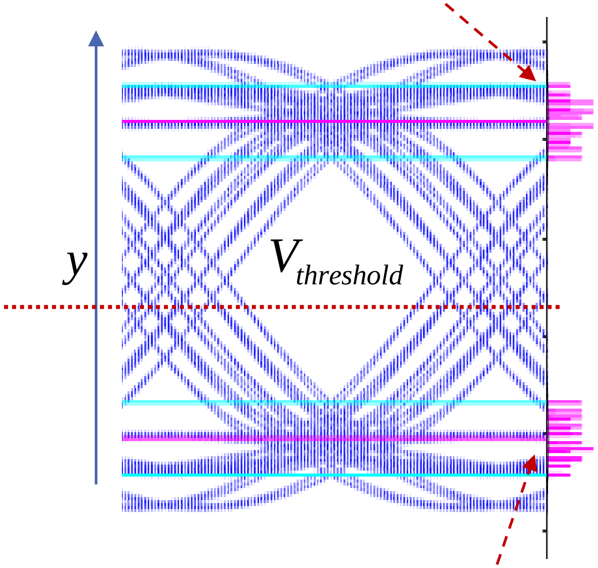
- PAM-2 is used to explain the model (M=2 to facilitate the description)
- The Q factor for a y value in the histogram as a function of the OMA_{tx_linear} and transmission penalties P_z is given by,

$$Q_a(y, P_Z) = \Delta \frac{y - V_{threshold}}{\sqrt{(P_Z n_R)^2 + (n_S)^2}} = \Delta \frac{y - V_{threshold}}{\sqrt{(P_Z n_R)^2 + (\frac{\Delta}{2}\sigma_S)^2}} \quad \text{B.1}$$



- Where y is the normalized received signal, $V_{threshold}$ is the decision threshold for the eye, $\Delta = OMA_{Tx\_outer\_linear} 10^{-Losses/10}$ is the OMA before the O/E, n_s is the signal (level) dependent noise (RIN, MPN, MN, baseline wander) for 0's or 1's, Q_t is the Q factor for a desired BER, P_z represents how much the AWGN can be increased from current values and still achieve the Q_t (more on Q_t in next slide)
- The AWGN, n_R ,is given by,

$$n_R = \frac{1}{M-1} \frac{OMA_{Rx\_outer\_linear}}{2Q_T} = \frac{10^{Receiver\_Sens - SECQ_{Tx}}}{2Q_T} \quad \text{B.2}$$

Computation of Margin & Penalties

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- The allowable power that can be used to mitigate for transmission penalties is the remaining power budget after connector losses and attenuation as shown,

$$P_{B-L} = \frac{OMA_{outer\_linear}}{OMA_{Rx\_outer\_linear}} L_{con} 10^{-att\,L/10} = \frac{\Delta}{OMA_{Rx\_outer\_linear}} \qquad \text{B.3}$$

- Using B.2 to B.3 in B.1, we obtain the Q factor for each trace in the sampled eye

$$Q_a(y, P_Z) = \frac{y - V_{threshold}}{\sqrt{(P_z \frac{OMA_{Rx\_outer\_linear}}{2Q_T \Delta})^2 + (0.5\sigma_S)^2}} = \frac{y - V_{threshold}}{\sqrt{(\frac{P_z}{P_{B-L}} \frac{1}{2Q_T})^2 + (0.5\sigma_S)^2}} \qquad \text{B.4}$$

- The BER is obtained by integrating the normalized PDFs for each level, 0 and 1 as shown,

$$BER(P_z) = 0.5[\int PDF(y,0) erfc(Q_{a\_01}(y, P_z)/\sqrt{2}) dy + \int PDF(y,1) erfc(Q_{a\_10}(y, P_z)/\sqrt{2}) dy] \qquad \text{B.5}$$

- where

$$\int PDF(y,0)dy = \int PDF(y,1)dy = 0.5$$

Computation of Margin & Penalties

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- At a given length, the actual BER of the system is obtaining by using all the power budget (minus losses). This is equivalent of setting P_z = 1 (0 dB)

$$BER_{Link} = BER(P_z = 1) \qquad \text{B.6}$$

- The Margin are obtained by solving B.5 (numerically) to obtain a BER that match the BER targeted.

$$BER(P_z = Margin) = BER_{target} = 0.5 erfc(Q_T / \sqrt{2}) \qquad \text{B.7}$$

- The total penalties are obtained using,

$$Penalties = P_{B-L} / Margin \quad \rightarrow \quad P_{Budget\_dB} - Losses - Margin\_dB \qquad \text{B.8}$$

- What is the meaning of Margin and Penalties in this model?
  - If there are no penalties (ISI, JITTER RIN, MPN…), the margin should be equal to the power budget minus losses. This is the ideal system with TDECQ=1 (0dB).
  - If the margin =0 all the budget (minus) losses is used to compensate for ISI, Jitter, RIN, MPN, and MN penalties

Computation of individual Penalties

- **The methods to compute ISI, Jitter, RIN, MPN, MN , BL are given below**
  - For the ISI penalty, the jitter and all signal dependent noises are set to zero and P_z is numerically found. $P_{ISI}=P_{B-L} - P_z$ (in dB);
  - For Jitter penalty, all signal dependent noises are set to zero and P_z is numerically found. $P_{ISI-Jitter}=P_{B-L} - P_z$ (in dB); $P_{jitter}=-P_{ISI}+P_{ISI-Jitter}$
  - For RIN penalty all signal dependent noises with exception of RIN are set to zero and P_z is numerically found. $P_{RIN}=P_{B-L} - P_z - P_{ISI-Jitter}$ (in dB)
  - For MPN penalty all signal dependent noises with exception of MPN are set to zero, P_z is numerically found. $P_{MPN}= P_{B-L} - P_z - P_{ISI-Jitter}$ (in dB)
  - For MN penalty all signal dependent noises with exception of MN are set to zero, P_z is numerically found. $P_{MN}= P_{B-L} - P_z - P_{ISI-Jitter}$ (in dB)
  - For BL penalty all signal dependent noises with exception of BL are set to zero, P_z is numerically found. $P_{BL}= P_{B-L} - P_z - P_{ISI-Jitter}$ (in dB)
  - Cross term penalties is the difference between total penalty (previous slide) minus the sum of all the individual penalties (in dB).

Computation of Margin & Penalties

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- **Summary of the model and differences compared to the worst-case eye?**
  - The Q factors are computed for each eye trace (at the center of the eye +/-Jitter).
  - The BER for each trace is computed
  - The total BER is the average of trace BER weighted using the PDFs of level 0 and 1
  - The margins are computed numerically. The total penalty is equal to the power budget minus losses minus margin (in dB).
  - The individual penalties are computed as shown in the previous slide
- **Fast checking with previous link models**
  - The margin and penalties solution for the proposed method (statistical eye are mainly numerically). However, if we select the worst case eye trace, the numerical solutions and *worst-case eye method* are identical.
  - For example if we use B.4 and make $Q_a = Q_t$

$$Q_a(y_{worst\_trace}, P_Z) = Q_T = \frac{0.5}{\sqrt{\left(\frac{P_z}{P_{B-L}}\frac{1}{2Q_T}\right)^2 + (0.5\sigma_S)^2}}$$

$$Penalties\_worst\_case - eye = \frac{P_z}{P_{B-L}} = \frac{1}{\sqrt{1-(Q_T\sigma_S)^2}}$$

Link Model Margin & Penalties for PAM-4

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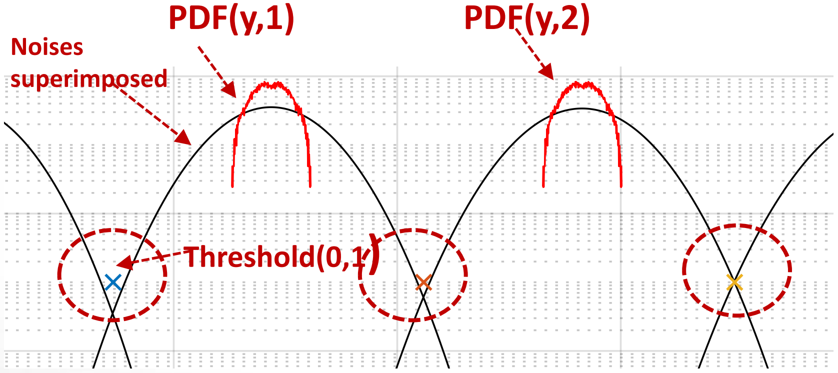
The model is now applied for PAM-4

$$Q_{01}(y,P_z)=\frac{y-threshold(0,1)}{\sqrt{\left(\frac{P_z}{P_{B-L}}\frac{OMA_{outer}}{6Q_T}\right)^2+(0.5\sigma_s(0))^2}}\qquad Q_{10}(y,P_z)=\frac{y-threshold(0,1)}{\sqrt{\left(\frac{P_z}{P_{B-L}}\frac{OMA_{outer}}{6Q_T}\right)^2+(0.5\sigma_s(1))^2}}$$

$$Q_{23}(y,P_z)=\frac{y-threshold(2,3)}{\sqrt{\left(\frac{P_z}{P_{B-L}}\frac{OMA_{outer}}{6Q_T}\right)^2+(0.5\sigma_s(2))^2}}\qquad Q_{32}(y,P_z)=\frac{y-threshold(2,3)}{\sqrt{\left(\frac{P_z}{P_{B-L}}\frac{OMA_{outer}}{6Q_T}\right)^2+(0.5\sigma_s(3))^2}}$$

- The thresholds are computed numerically from the histograms. They are placed at the locations where the PDFs of each level intercept.
- The traditional equations for threshold does not apply here due to the arbitrary shape of the PDFs



Link Model Margin & Penalties

The *SER* is computed as follows,

$$SER(P_z) = 0.5[\int PDF(y, L0) erfc(Q_{01}(y, P_z)/\sqrt{2})dy +$$

$$\int PDF(y, L1)\{erfc(Q_{10}(y, P_z)/\sqrt{2}) + erfc(Q_{12}(y, P_z)/\sqrt{2})\}dy +$$

$$\int PDF(y, L2)\{erfc(Q_{21}(y, P_z)/\sqrt{2}) + erfc(Q_{23}(y, P_z)/\sqrt{2})\}dy +$$

$$\int PDF(y, L3) erfc(Q_{32}(y, P_z)/\sqrt{2})dy]$$

Where the PDFs of the signal for each level satisfies

$$\int PDF(y, L0)dy = \int PDF(y, L1)dy = \int PDF(y, L2)dy = \int PDF(y, L3)dy = 0.25$$

The BER is computed assuming Gray coding

$$BER(P_z) = 0.5 SER(P_z)$$

Link Model Margin & Penalties

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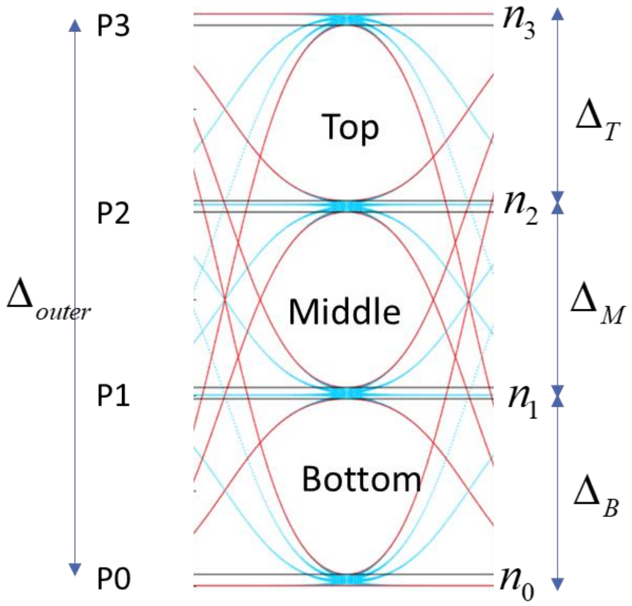

- The BER of the system is given by,

$$BER_{Link} = BER(P_z = 1)$$

- The Margins are computed numerically by finding the P_z value that makes the link BER equal to the target BER. Provide the margin

$$BER(P_z = Margin) = BER_{target} = 0.5erfc(Q_T / \sqrt{2})$$

- Therefore all the eyes are solved at once. There is only one margin value for the system instead of three margins for each eye!

- The penalty for all signal dependent noises is given by,

$$Penalties = P_{Budget} - Margin$$

- The individual ISI, Jitter, RIN... penalties are computed using the same methodology as previously shown for the PAM-2 case

Annex IV Relationship of Link Model with TDECQ

TDECQ from link model margin derivation

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The value of TDECQ can be computed as follows,

$$TDECQ = \frac{OMA_{outer}}{\sqrt{n_G{}^2 + n_R{}^2}\,6Q_T} = \frac{OMA_{outer}}{n_T\,6Q_T}$$

Where n_G is the maximum noise amount that can be added (before equalizer) while maintaining the BER target, . Therefore,

$$n_T = \sqrt{\left(\frac{OMA_{outer} M\arg in_{TDECQ}}{6P_{B-L}Q_T}\right)^2 - n_R{}^2 + n_R{}^2} = \left(\frac{OMA_{outer} M\arg in_{TDECQ}}{6P_{B-L}Q_T}\right)$$

$$TDECQ = \frac{OMA_{outer}}{\frac{OMA_{outer}}{6}\frac{M\arg in_{TDECQ}}{P_{B-L}Q_T}6Q_T} = \frac{P_{B-L}}{M\arg in_{TDECQ}} \approx Penalties_{At\,2m,with\_BW\_TDECQ}$$

Notes:

- TDECQ in this computation only consider the noises at 2 m using the specified BW.
- Therefore is does not guaranty that longer reaches with more noise will work.
- Moreover, is a receiver with better sensitivity is used $n_r' = X\, n_r$, where X<1, the TDECQ is also should reduced by X