

# Link Model Spreadsheet for Optical PAM-4 Channels

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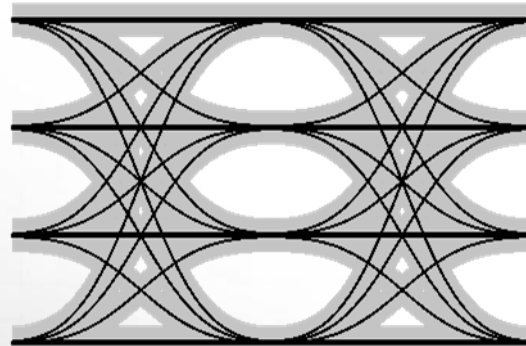
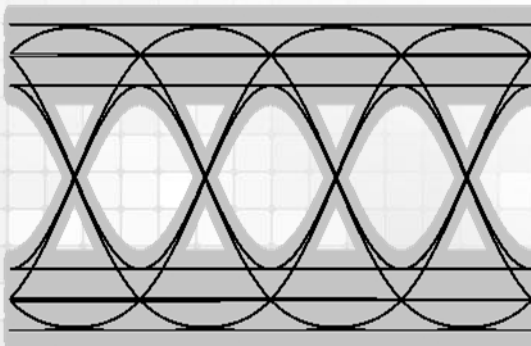
Next-generation 200 & 400 Gb/s MMF PHYs  
Rosemont, March. 2018

## Outline

- Background
- Objectives
- New Models for PAM-N,
  - ISI and Jitter penalties for multilevel signal
  - Eye skew penalties as a Deterministic Jitter
  - Noise models
    - RIN, MPN, and other penalties for multi-level signals
- Link Model Spreadsheets
  - Current spreadsheet structure and limitation
  - VBA functions to support more complex models
  - Proposed link model spreadsheet for FC-P1-7 and 802.3cm PAM4 applications
  - Proof of concept
- Discussion and Summary

## Background

- Link model spreadsheets have been used in IEEE and Fibre Channel as illustrative examples of optical links reaches and power budgets.
- Recent IEEE and Fibre Channel PMDs have not adopted link model spreadsheets
  - PI-7 64GFC-SW-SW, IEEE 802.3cd ...
- Implementation equalized PMA-4 eyes and penalties in a spreadsheet, i.e, Excel spreadsheet, could be challenging.
  - Simplicity of script based programs such as Python or Matlab are difficult to translate to a spreadsheet.
  - Slow computation and graphic response of spreadsheet.



## Background

- 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
  - For Matlab 15-263v0
  - An Excel VBA was proposed in T11-2016-065v0
    - Fully implemented PI-6P (32GFC NRZ)

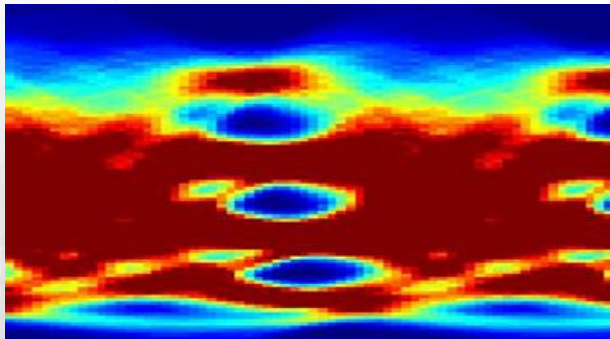
## Objective

- Discuss the benefits of having a link model spreadsheet as a guidance during the standardization process of new PMDs
- TDECQ suitable for production test, however,
  - Based on assumptions that might not represent actual channels
    - Proxy for PDFs, Bessel-Thomson filter representing MMF and receiver,
    - Thresholds from OMAs (sensitive to small variations).
    - Sampling points and effects of eye skew
- A link model spreadsheet can be easy to use and share
  - Real-time results enable collaboration among participants
  - Enable relative comparison of PMD solutions
    - Comparing penalties due to data rate differences, wavelengths (Pimpinella\_NGMMF\_02\_0118), reaches
    - Compare additional power budget penalties between MMF PMD from IEEE 802.3cd vs Fibre ChannelPI-7
    - Compare penalties between modulation formats (PAM vs NRZ)

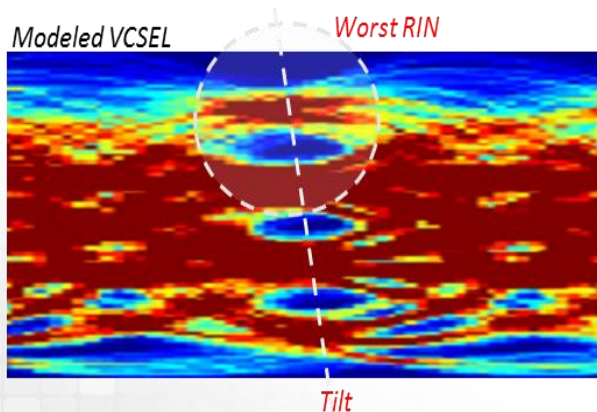
# New Penalties for Optical PAM-4

- Modeling based on multi-mode rate equation is accurate to predict VCSEL performance.
  - However, it is computational demanding and impractical for a spread-sheet link model.
- Gaussian approximation for multi-level channels use analytical expressions
  - They could be easily implemented in link models.
  - However, Gaussian models need additional consideration to represent real channels.

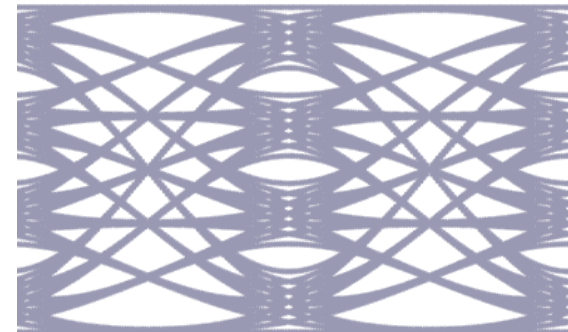
*Measured VCSEL*



*Modeled VCSEL*



*Gaussian Approx*



# The Gaussian Channel

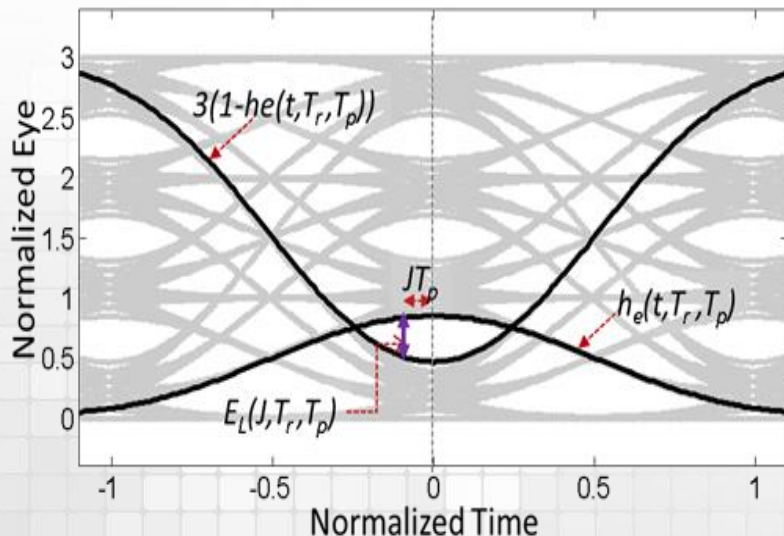
- The response to a rectangular pulse of duration equal to  $T_p$ , is given by,

$$h_e(t, T_r, T_p) = 0.5 \left[ \operatorname{erf} \left( k \frac{[2t + T_p]}{T_r} \right) + \operatorname{erf} \left( k \frac{[-2t + T_p]}{T_r} \right) \right]$$

where  $T_p$  is the symbol period, and  $T_r$  is the 10-90% overall system rise time which comprises the laser, fiber, and the photo-receiver response.

- For PAM-M where  $M=4$ , the worst case bottom eye represented by  $E_L$ , shows the combined effect of ISI and Jitter degradation.

$$E_L(J, T_r, T_p) = h_e(0.5J T_p, T_r, T_p) - (M - 1) [1 - h_e(0.5J T_p, T_r, T_p)]$$



## Power Penalty

$$P_{ISI+J}(J, T_r, T_p) = -10 \log_{10}(E_L(J, T_r, T_p))$$

# ISI-Jitter Penalties for equalization of PAM-4: Equalizer example with 3 tap

- The response for an equalized channel is given by,

$$h_f(t, T_r, T_p) = c_0 h_e(t, T_r, T_p) + c_1 h_e(t - T_p, T_r, T_p) + c_{-1} h_e(t + T_p, T_r, T_p)$$

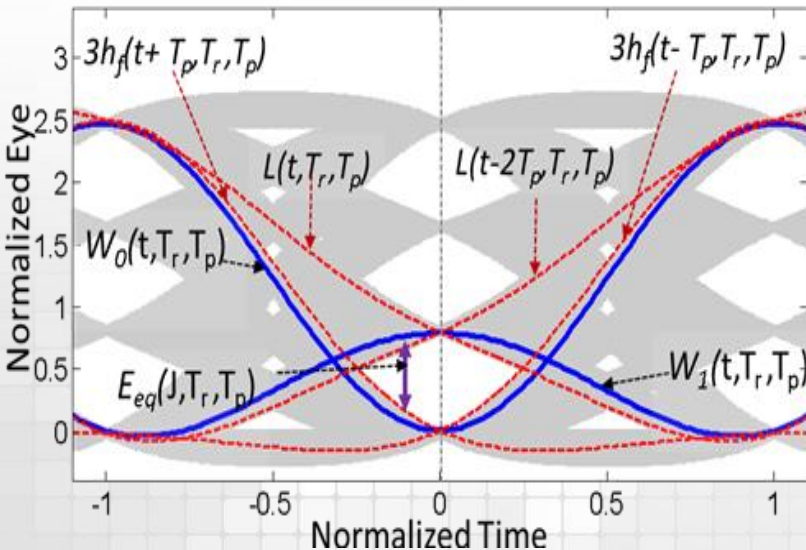
- For simplicity, only 3 taps are shown here

$$c_0 = 1; \quad c_1 = c_{-1} = \frac{h_1}{h_0} \left( \frac{2h_1^2 - h_0^2 + \sigma^2}{h_0^2 - h_1^2 + \sigma^2} \right);$$

– where,  $h_0 = h_e(0, T_r, T_{PAM})$  and  $h_1 = h_e(T_{PAM}, T_r, T_{PAM})$ .

The worst eye height is given by,

$$E_L^{t=0}(T_r, T_p) = W_1(0, T_r, T_p) - W_0(0, T_r, T_p) \\ \approx h_f(0, T_r, T_p) + 2(M-1)[h_f(2T_p, T_r, T_p) - h_f(T_p, T_r, T_p)]$$



The worst eye width is given by L sequences:

$$E_{Eq}(J, T_r, T_p) \approx E_{eq}^{t=0}(T_r, T_p) \max \left( 2 \frac{L(|0.5JT_p|, T_r, T_p)}{L(0, T_r, T_p)} - 1, 0 \right)$$

## Power Penalty

$$P_{ISI+J} = 10 \log_{10}(E_{Eq}(J, T_r, T_p))$$



## Eye skew as deterministic jitter

- Eye skew penalties can be incorporated as an additional of deterministic jitter.

$$P_{ISI + J} = 10 \log_{10} \left( Eq \left( J + \left( \frac{\Delta T}{T_p} \right), Tr, Tp \right) \right)$$

Eye skew dependence on transmitted symbol

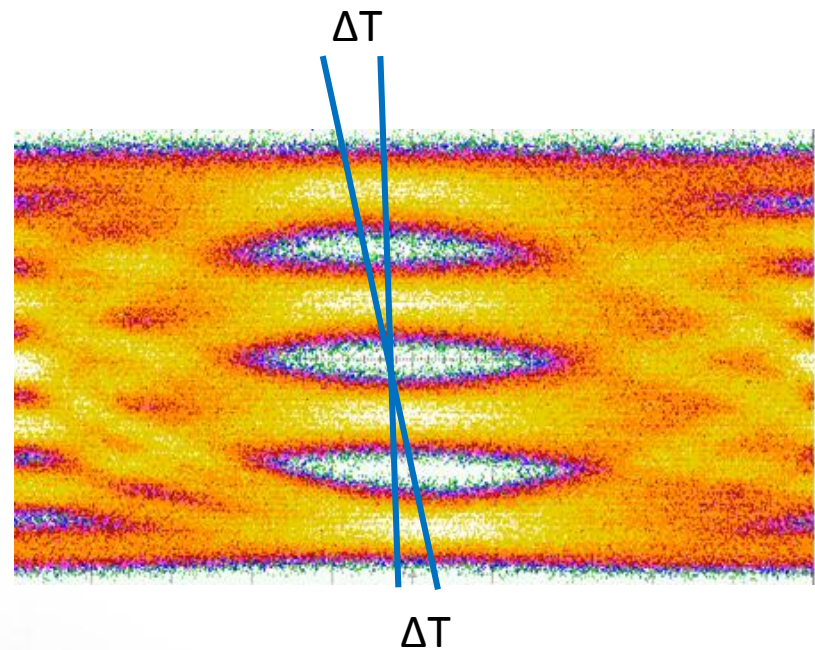
30303



+ 020202



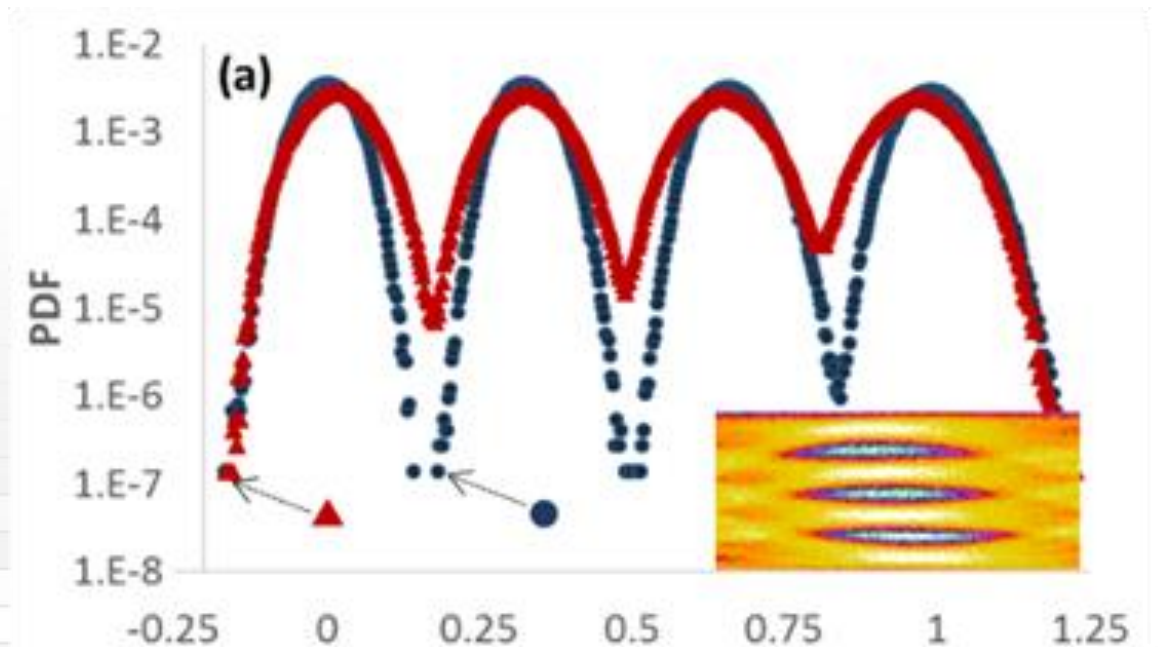
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# Noise Penalties (work in progress)

- Rescale RIN and signal dependent noise due to multilevel symbols
- Higher level signals have more penalties

$$\Delta N_o = 10 \log_{10} \left( \frac{s_W + \sqrt{s_W + s_{RIN-OOK}}}{\sqrt{F_W s_W + \left(\frac{M-2}{M-1}\right)^2 F_{RIN} s_{RIN-OOK}} + \sqrt{F_W s_W + F_{RIN} s_{RIN-OOK}}} \right)$$



# Link Model Spreadsheet

# Limitations of Link Model Spreadsheet

- A significant portion of the worksheet is used for intermediary computations

**Mostly Input parameters**

**Eyes & penalties**

**Mostly intermediary steps for penalties or plotting**

Most of the results. Almost all cells use an equation

Mostly intermediary steps for penalties or plotting. Almost all cells use an equation

- VBA code example for:
  - Handling all power budget penalties and equalization up to 5 taps.
  - Fully implemented in VBA for OOK or PAM4
  - Dispersion Module and Equalizer module for 3 taps shown as an example.

```
-----  
Sub Dispersion_Module()  
L = Reach  
D1 = 0.25 * D_slope * lambda_c * (1 - (lambda_z / lambda_c) ^ 4)  
D2 = 0.7 * D_slope * Spectral_Width  
D = (D1 ^ 2 + D2 ^ 2) ^ 0.5 'ps/nm km  
BWcd = 0.187 * 10 ^ 6 / (L * Spectral_Width * D)  
Ts = Ts_20_80 * 1.518 '%ps converted to 10%-90%  
BWmc = Sqr(1 / ((1 / BWme * L) ^ 2 + (1 / BWcd) ^ 2))  
Tr = c2 * 10 ^ 3 / BWrec  
Te = (Ts ^ 2 + 10 ^ 6 * (c1 / BWmc) ^ 2) ^ 0.5  
Tc = (Te ^ 2 + Tr ^ 2) ^ 0.5  
  
End Sub  
-----  
Sub Compute_Taps()  
  
b1 = 0: b2 = 0  
arg = 2.563 / 2 / (2 ^ 0.5) * (Teff / Tc)  
If EQ_flag = 1 Then  
    h0 = (0.5 * (WorksheetFunction.Erf(arg * (1)) - WorksheetFunction.Erf(arg * -1)))  
    h1 = (0.5 * (WorksheetFunction.Erf(arg * (3)) - WorksheetFunction.Erf(arg * 1)))  
    b1 = h1 / h0 * (2 * h1 ^ 2 - h0 ^ 2) / (h0 ^ 2 - h1 ^ 2)  
    b2 = 0  
End If  
.....
```

- VBA code example for 5 tap equalizer:
  - Handles all power budget penalties and equalization up to 5 taps.
  - Fully implemented in VBA

```
'%%%% Compute Equalizers
Sub Compute_Taps()

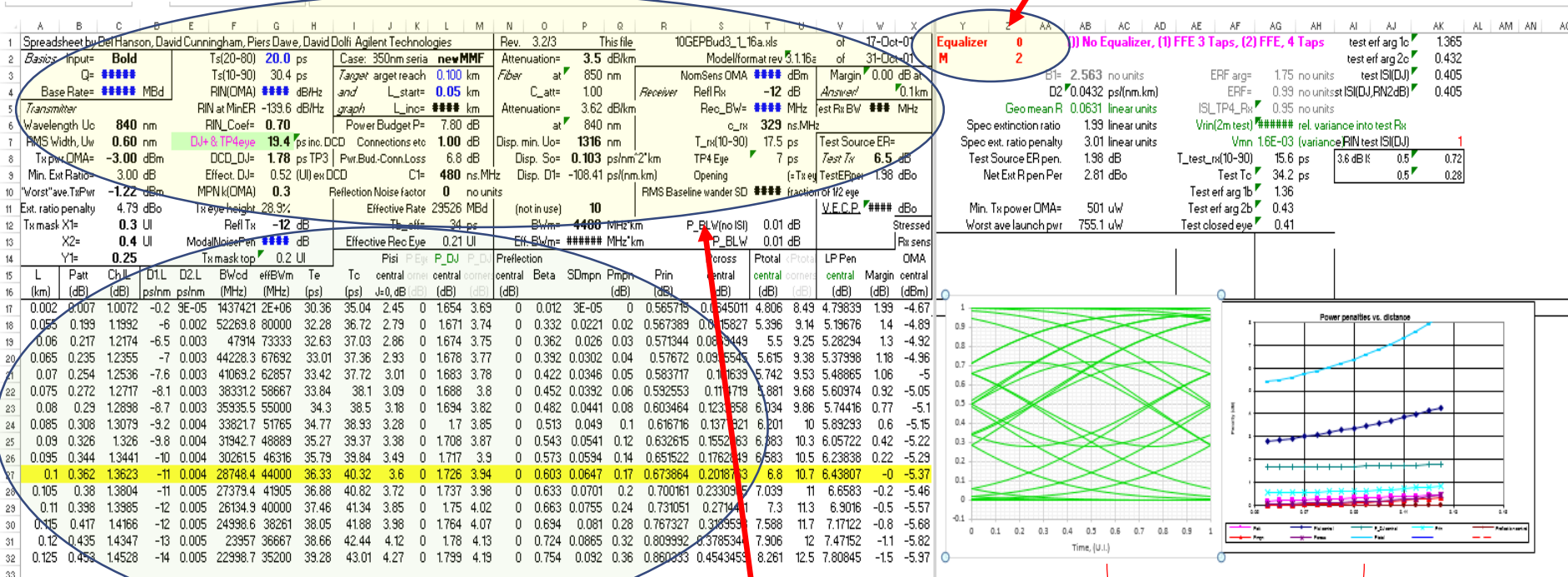
b1 = 0: b2 = 0
arg = 2.563 / 2 / (2 ^ 0.5) * (Teff / Tc)
If EQ_flag = 1 Then
    h0 = (0.5 * (WorksheetFunction.Erf(arg * (1)) - WorksheetFunction.Erf(arg * -1)))
    h1 = (0.5 * (WorksheetFunction.Erf(arg * (3)) - WorksheetFunction.Erf(arg * 1)))
    b1 = h1 / h0 * (2 * h1 ^ 2 - h0 ^ 2) / (h0 ^ 2 - h1 ^ 2)
    b2 = 0
End If
'%%5 taps
If EQ_flag = 2 Then
    h0 = (0.5 * (WorksheetFunction.Erf(arg * (1)) - WorksheetFunction.Erf(arg * -1)))
    h1 = (0.5 * (WorksheetFunction.Erf(arg * (3)) - WorksheetFunction.Erf(arg * 1)))
    h2 = (0.5 * (WorksheetFunction.Erf(arg * (5)) - WorksheetFunction.Erf(arg * 3)))
    deno = h0 ^ 5 + 2 * h0 ^ 4 * h2 - 3 * h0 ^ 3 * h1 ^ 2 + h0 ^ 3 * h2 ^ 2 - 2 * h0 ^ 2 * h1 ^ 2 * h2 - 2 * h0 ^ 2 * h2 ^ 3 + 2 * h0 * h1 ^ 4 + 9 * h0 *
    b2 = -(h0 ^ 4 * h2 - h0 ^ 3 * h1 ^ 2 + 2 * h0 ^ 3 * h2 ^ 2 - 5 * h0 ^ 2 * h1 ^ 2 * h2 + 3 * h0 * h1 ^ 4 + 2 * h0 * h1 ^ 2 * h2 ^ 2 - 4 * h0 * h2 ^ 4
    b1 = -(h0 ^ 4 * h1 - 2 * h0 ^ 2 * h1 ^ 3 - 3 * h0 ^ 2 * h1 * h2 ^ 2 + 8 * h0 * h1 ^ 3 * h2 + 2 * h0 * h1 * h2 ^ 3 - 2 * h1 ^ 5 - 6 * h1 ^ 3 * h2 ^ 2
End If
End Sub
```

# Modified Spreadsheet



- No equations in the results cells. VBA module updates results when an input is changed

Two new Inputs for Equalization Type and Signal Levels



Most of the results. Each cell contains a value not a function

Mostly Input parameters. Any change triggers a recalculation of the results

Plots

# Examples



- To be shown during presentation

AutoSave Off | Link\_Model\_VBA\_v3.xlsm - Excel | Jose Castro | Tell me what you want to do | Share

File Home Insert Page Layout Formulas Data Review View Developer Add-ins Help PowerPivot Team Design Format

Chart 2

Insert Function

Rev.	3/2/3	This file	10GEBud3_1_16a.xls	of	17-Oct-01
Attenuation=	3.5 dB/km	Model/format rev	5.1.116a	of	31-Oct-01
Fiber	at 850 nm	NomSens CMA	-11.00 dBm	Margin	0.00 dB at 0.1 km
Attenuation=	3.62 dB/km	Rec_BW=	19.00 MHz	Answe	1.0 km
Disp. min. Uo=	1316 nm	c_rx	329 ns.MHz	Test Source ER=	
Disp. Sps=	0.1028 ps/nm*2*km	TP4 Eye	7 ps	Test Tx	6.5 dB
Disp. D1=	-108.41 ps/(nm.km)	Opening	(+Tx eye)	Test/Er eye	1.98 dBo
		RMS Baseline wander SD	0.012 fraction of 12 eye	V.E.C.P. #####	dBo
		BWm=	4400 MHz*km	P_BLW(no ISI)	0.00 dB
		Erf BWm=	4.4E+03 MHz*km	P_BLW	0.00 dB

Equalizer	2	(0) No Equalizer, (1) FFE 3 Taps, (2) FFE 5 Taps	test erf arg 1c	1.088
M	2		test erf arg 2c	0.740
EYE TILT DJ (ps)	0	B1= 2.563 no units	test ISI(DJ)	0.581
		D2' 0.0396 ps/(nm.km)	test ISI(DJ,RN2dB)	0.581
		Geo mean R 0.0631 linear units		
		ISI_TP4_Rx	0.94 no units	
		Spec extinction ratio	1.99 linear units	
		Spec ext. ratio penalty	3.01 linear units	
		Net ExR pen Per	2.81 dBo	
		Min. Tx power OMA=	977 uW	
		Worst ave launch pwr	1472.3 uW	

LP Pen	0.00 dB	Stressed	0.00 dB
LP Pen	0.00 dB	Stressed	0.00 dB

LP Pen	0.00 dB	Stressed	0.00 dB
LP Pen	0.00 dB	Stressed	0.00 dB

TP4 Eye Width Extension: J Patricia Avago Technologies	Reach	Peye	TP1 RJ, UI = 0.110	3.81 ps for BER=E-12	###	1.19	-1.46	-3.00	0.00	0.00	0.00	-0.51	-0.06	-3.23	-4.25	-3.23	5.83
Reach	db	TP1 RJrms, UI = 0.0082	0.28 ps	###	###	1.19	-1.47	-3.04	0.00	0.24	-0.02	-0.51	-0.07	-3.69	-5.31	-3.55	6.29
63	-2.98	TP1 RJ (@BER), UI = 0.062	2.13 ps	###	###	1.19	-1.48	-3.05	0.00	0.24	-0.02	-0.51	-0.07	-3.76	-5.39	-3.62	6.36
44	BER = 1.1E-04	TP1 DJ, UI = 0.110	3.81 ps	###	###	1.20	-1.48	-3.06	0.00	0.24	-0.03	-0.52	-0.08	-3.84	-5.47	-3.69	6.44
46	3.7750	TP3 DJ wo ISI, UI = 0.240	8.30 ps	###	###	1.22	-1.48	-3.08	0.00	0.24	-0.03	-0.52	-0.09	-3.92	-5.56	-3.78	6.52
47	Q(TJ@BER)	TP3.5 DJisi, UI = 0.039	1.35 ps	###	###	1.23	-1.49	-3.09	0.00	0.24	-0.03	-0.55	-0.12	-4.22	-5.91	-4.08	6.82
48	6.7385	DJ at TP4, UI = 0.319	11.04 ps	###	###	1.25	-1.49	-3.11	0.00	0.24	-0.04	-0.56	-0.10	-4.11	-5.78	-3.97	6.71
49	Q(Jn)	RJ(link noise), UI = 0.769	26.6 ps	###	###	1.27	-1.50	-3.13	0.00	0.24	-0.04	-0.58	-0.12	-4.22	-5.91	-4.08	6.82
50	2.0537	Cum RJ(TP4), UI = 0.771	26.7 ps	###	###	1.30	-1.51	-3.15	0.00	0.24	-0.04	-0.57	-0.13	-4.35	-6.05	-4.21	6.95
51	0.85	TP4 TJ (@BER), UI = 1.090	37.7 ps	###	###	1.32	-1.51	-3.18	0.00	0.24	-0.05	-0.58	-0.15	-4.48	-6.20	-4.34	7.08
		TP4 I2, UI = 0.691	23.9 ps	###	###	1.35	-1.52	-3.21	0.00	0.24	-0.05	-0.60	-0.17	-4.63	-6.37	-4.49	7.23

Notes | BaseOM4(1) | BaseOM4\_vba | Sheet1 | BaseOM4(1c) | OM4(2) | OM3(1) | 10GbE Notes | 850S2000

Ready | 9:45 PM | 2/6/2018



# Examples



- To be shown during presentation

The screenshot displays an Excel spreadsheet titled 'Link\_Model\_VBA\_v3.xlsm' with the following content:

Rev	3/23	This file	10GEPBv3_1_16a.xls	of	17-Oct-01
Model	Format	rev	S 116a	of	31-Oct-01
Attenuation	3.5 dB/km	Fiber	at	850 nm	Receiver
Ref R	Ref R	Ref R	-12 dB	Margin	0.00 dB
Attenuation	3.62 dB/km	at	840 nm	Test Rx BW	21.675 MHz
Disp. min. Uv	1316 nm	Disp. min. Uv	1316 nm	Test Source ER	Test Tx
Disp. D1+	108.41 ps/(nm.km)	Disp. D1+	108.41 ps/(nm.km)	Opening	(+Tx Eye)
Eff. BWm	4400 MHz*km	Eff. BWm	4.4E+03 MHz*km	P_BLW(no ISI)	0.00 dB
Eff. BWm	4.4E+03 MHz*km	Eff. BWm	4.4E+03 MHz*km	P_BLW	0.00 dB

Key parameters and values:

- Base Rate:** 28900.0 Mbd
- Wavelength:** 840 nm
- RMS Width, Uv:** 0.55 nm
- Tx pwr OMA:** -0.10 dBm
- Min. Ext Ratio:** 3.00 dB
- Worst Tx Pwr:** 1.68 dBm
- Ext. ratio penalty:** 4.79 dB
- Tx mask top:** 0.2 UI

The spreadsheet also contains a 'Jitter' section with the following data:

Reich	Reach	Peye	TP1 RJ, UI	UI	TP1 RJrms, UI	UI	TP1 RJ(@BER), UI	UI	TP1 DJ, UI	UI	TP3 DJ wo ISI, UI	UI	TP3 DJ, UI	UI	DJ at TP4, UI	UI	RJ(link noise), UI	UI	Cum RJ(TP4), UI	UI	TP4 TJ Target	UI	TP4 TJ(@BER), UI	UI	TP4 TJ, UI	UI
0.111	0.40	1.90	-12.0	0.00	28.359	39.787	36	40	1.90	##	2.20	0.72	0	-0.63	0.02	0.02	0.13	0.04	4.8	5.5	4.4	-0.2	-2.3			

The graphs on the right show 'Power penalties vs. distance' and 'Jitter' plots with various data series representing different simulation metrics.

## Summary and Conclusions

- Discussed the benefits of having a link model spreadsheet as a guidance during the standardization process of new PMDs
  - Sharing and collaboration
  - Real-time results (click and see)
  - Enable relative comparison of PMD solutions
    - Comparing allowable reaches and penalties due to:
      - data rates, wavelengths, BER, modulation formats ..
- Develop models for equalized PAM-4 channels
  - Presented models for ISI, Jitter and Power dependent noise
  - New functions for Multi-level signals (VBA or dlls)
  - Still more work to do...
- Invite collaboration to develop a shared model

# QUESTIONS

# BACKUP

# TDECQ modeling presented in fiber channel in 2017

Sensitivity to thresholds...

Eye Statistics

