Link Model Spreadsheet for Optical PAM-4 Channels

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Next-generation 200 & 400 Gb/s MMF PHYs
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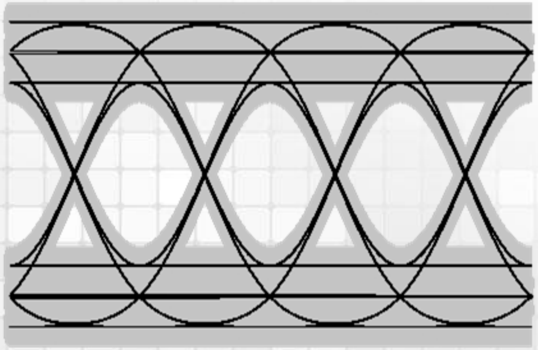
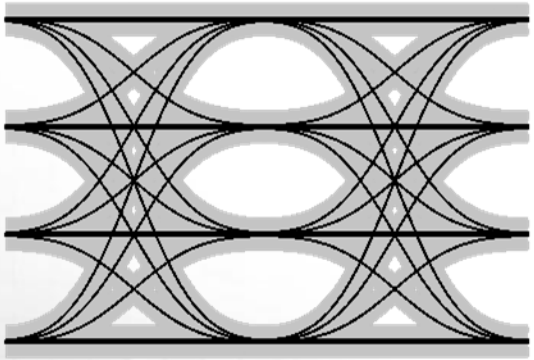
Outline

- 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-PI-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)

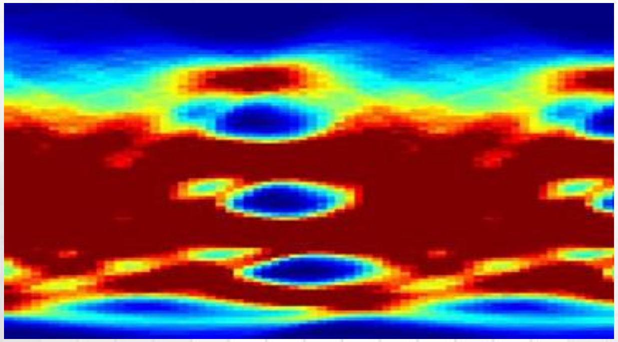
Objective

- 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)

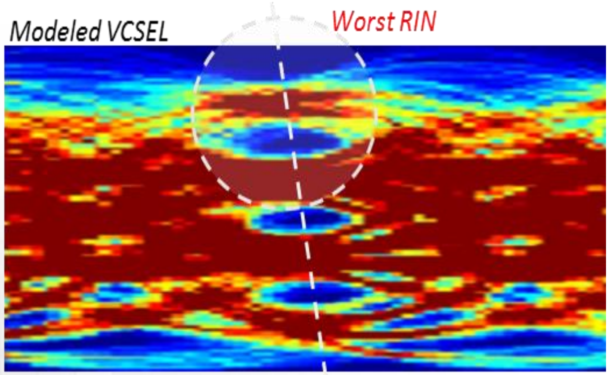
New Penalties for Optical PAM-4

- 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.

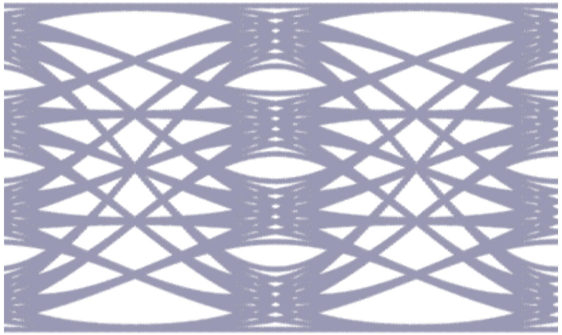
Measured VCSEL



Modeled VCSEL



Gaussian Approx



The Gaussian Channel

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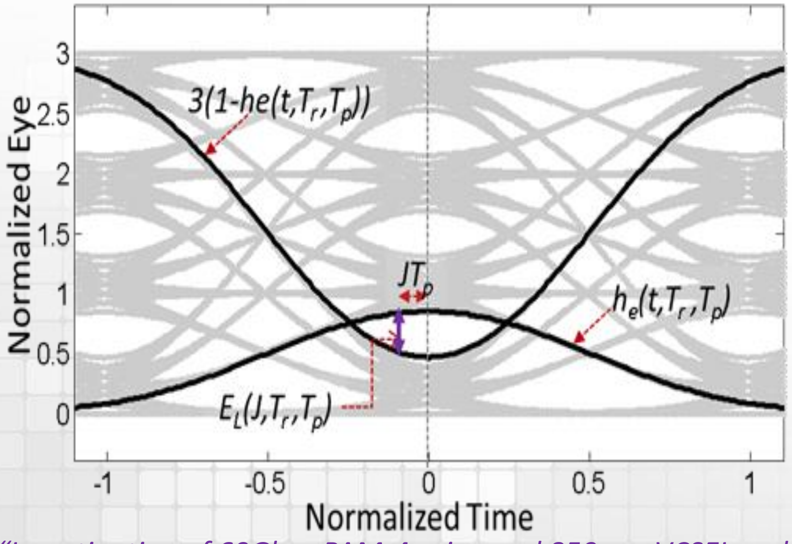
- The response to a rectangular pulse of duration equal to T_p, is given by,

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

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.

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



<u>Power Penalty</u>

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

From "Investigation of 60Gbps PAM-4 using and 850 nm VCSEL and MMF, "IEEE, Journal of Lightwave Tech, Vol. 34, Issue 16, pp. 3825-3836 (2016)

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

- The response for an equalized channel is given by,

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

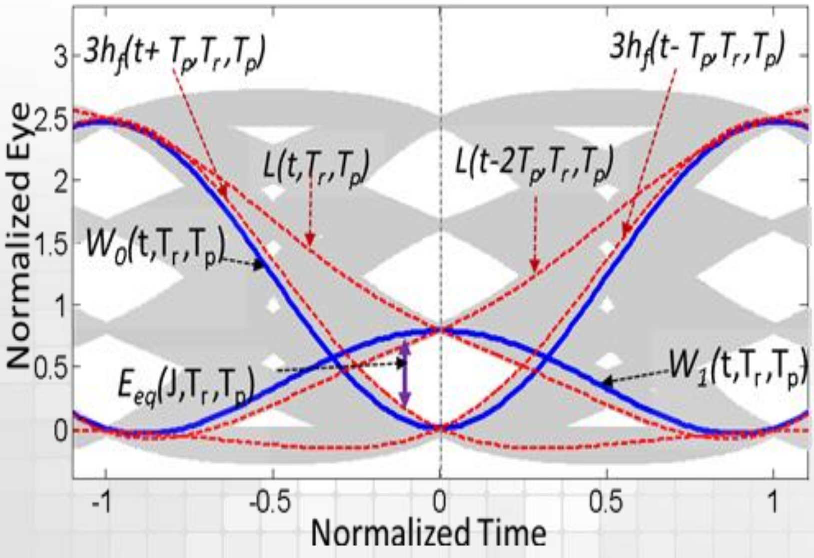
- For simplicity, only 3 taps are shown here

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

  - 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:

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

<u>Power Penalty</u>

$$P_{ISI+J} = 10log10(EEq(J,Tr,Tp))$$

From "Investigation of 60Gbps PAM-4 using and 850 nm VCSEL and MMF, "IEEE, Journal of Lightwave Tech, Vol. 34, Issue 16, pp. 3825-3836 (2016)

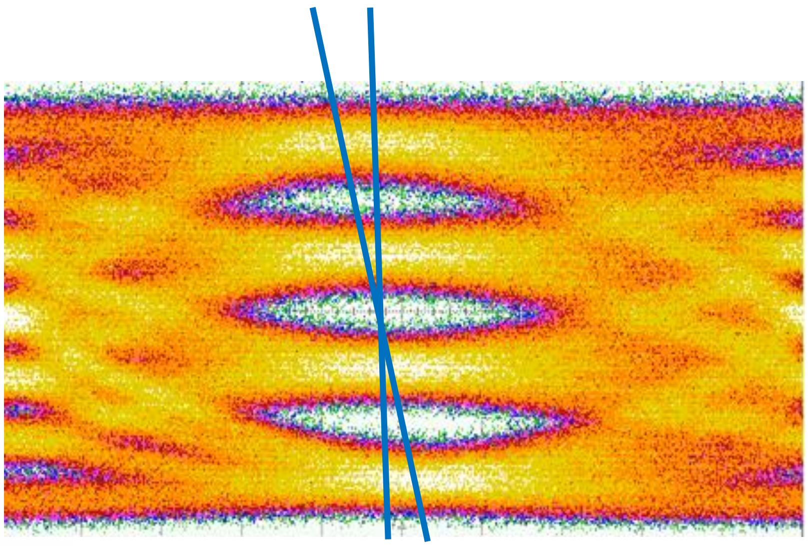
Eye skew as deterministic jitter

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

$$P_{ISI\ +\ J} = 10log10(Eq(J + \left(\frac{\Delta T}{T_p}\right), Tr, Tp))$$

Eye skew dependence on transmitted symbol

30303 | + 020202 | + 010101



See t11-2016-327v0

Noise Penalties (work in progress)

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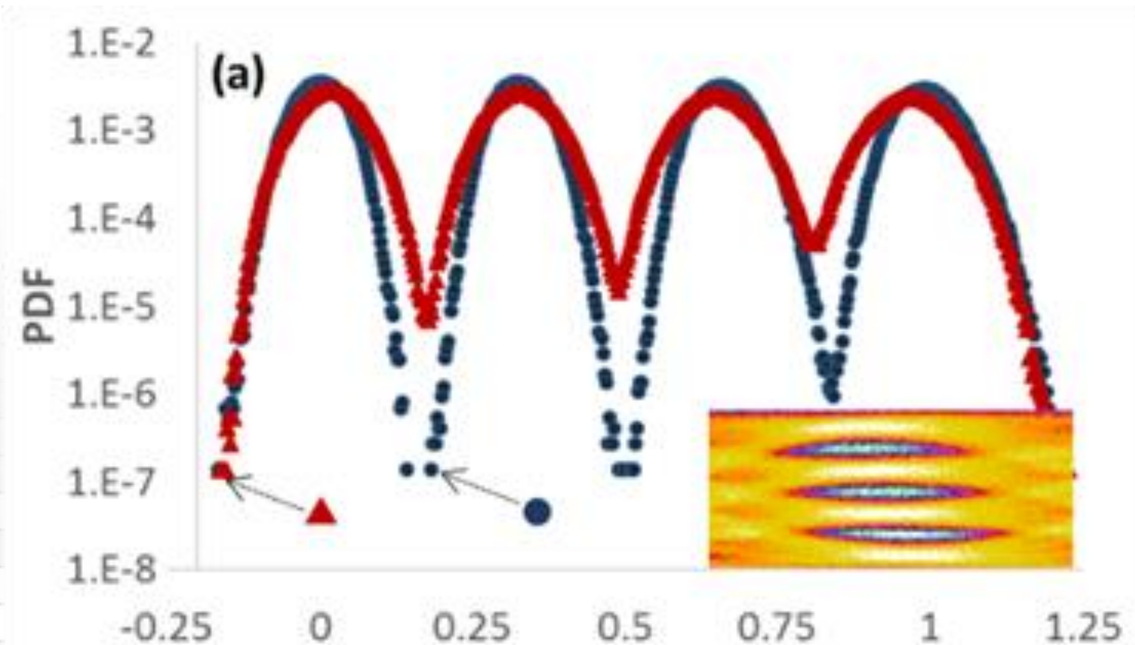
- Rescale RIN and signal dependent noise due to multilevel symbols
- Higher level signals have more penalties

$$\Delta No = 10\log_{10}\left(\frac{s_W + \sqrt{s_W + s_{RIN-OOK}}}{\sqrt{F_W s_W + \left(\frac{M-2}{M-1}\right)^2 F_{RIN} s_{RIN-OOK}} + \sqrt{F_W s_W + F_{RIN} s_{RIN-OOK}}}\right)$$



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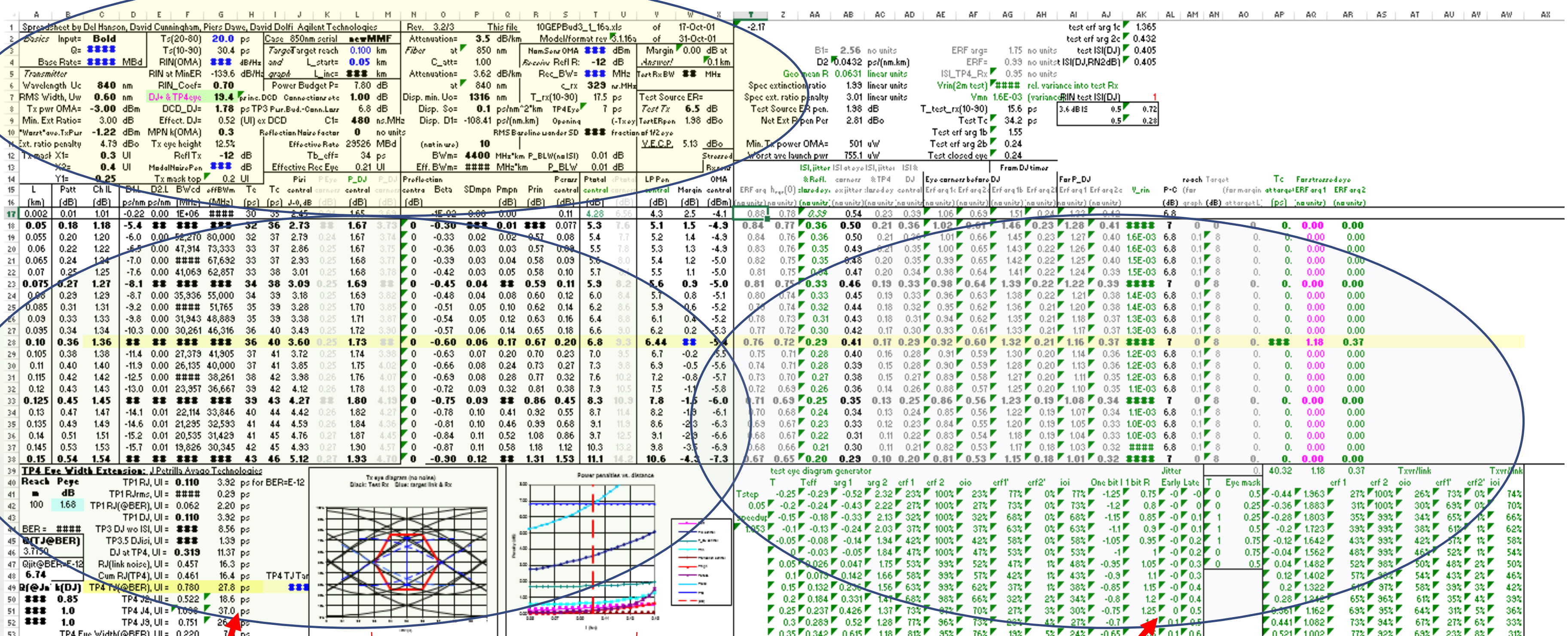
Link Model Spreadsheet

Limitations of Link Model Spreadsheet

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

Mostly Input parameters



Eyes & penalties

Most of the results. Almost all cells use an equation

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

Modified Spreadsheet

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- 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
```

Modified Spreadsheet

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

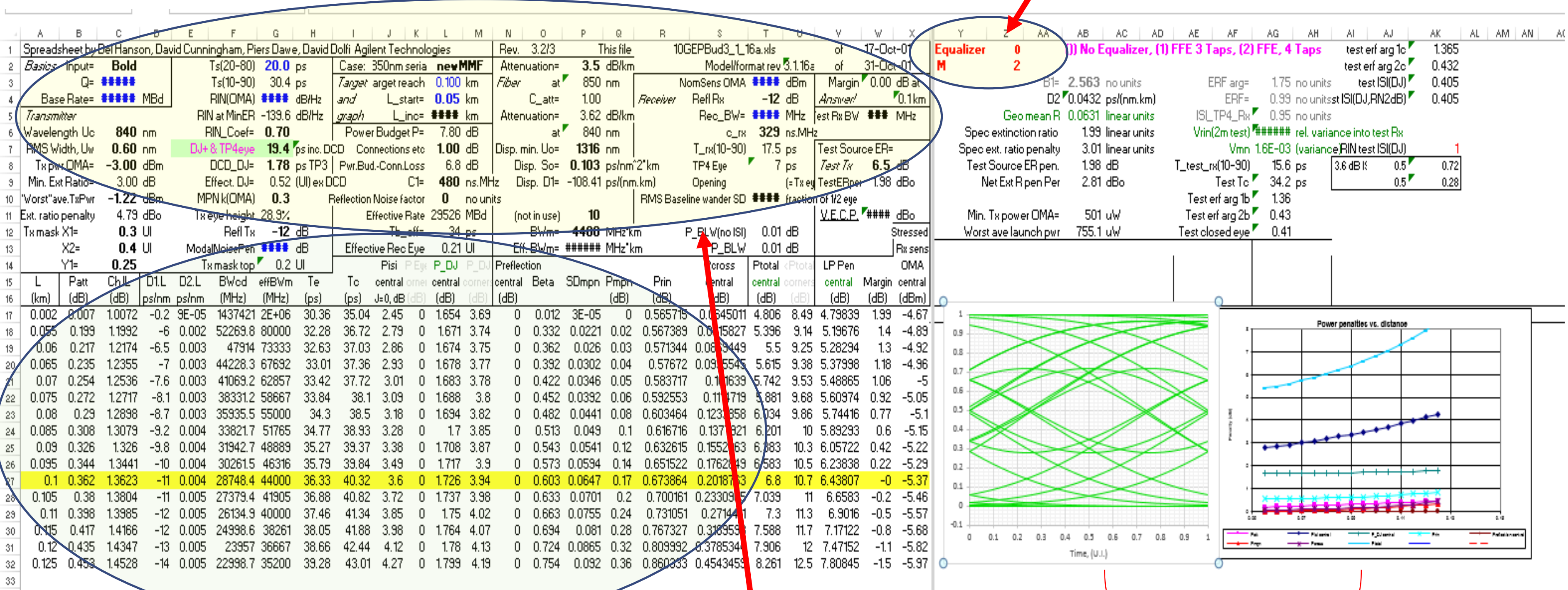
```
'%%%%% Compute Equalizers
Sub Compute_Taps()

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

PANDUIT

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

Two new Inputs for Equalization Type and Signal Levels



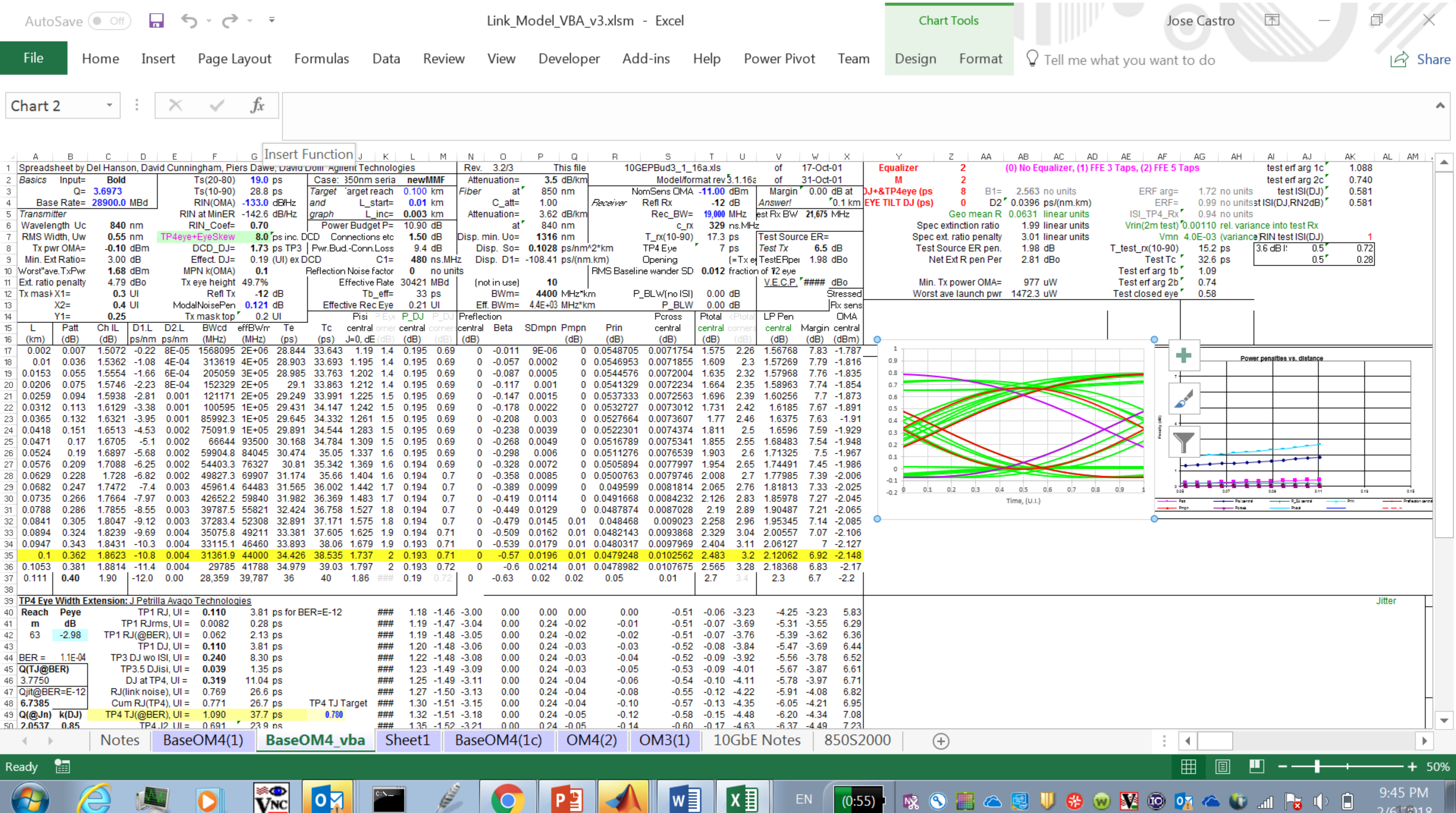
Plots

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

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

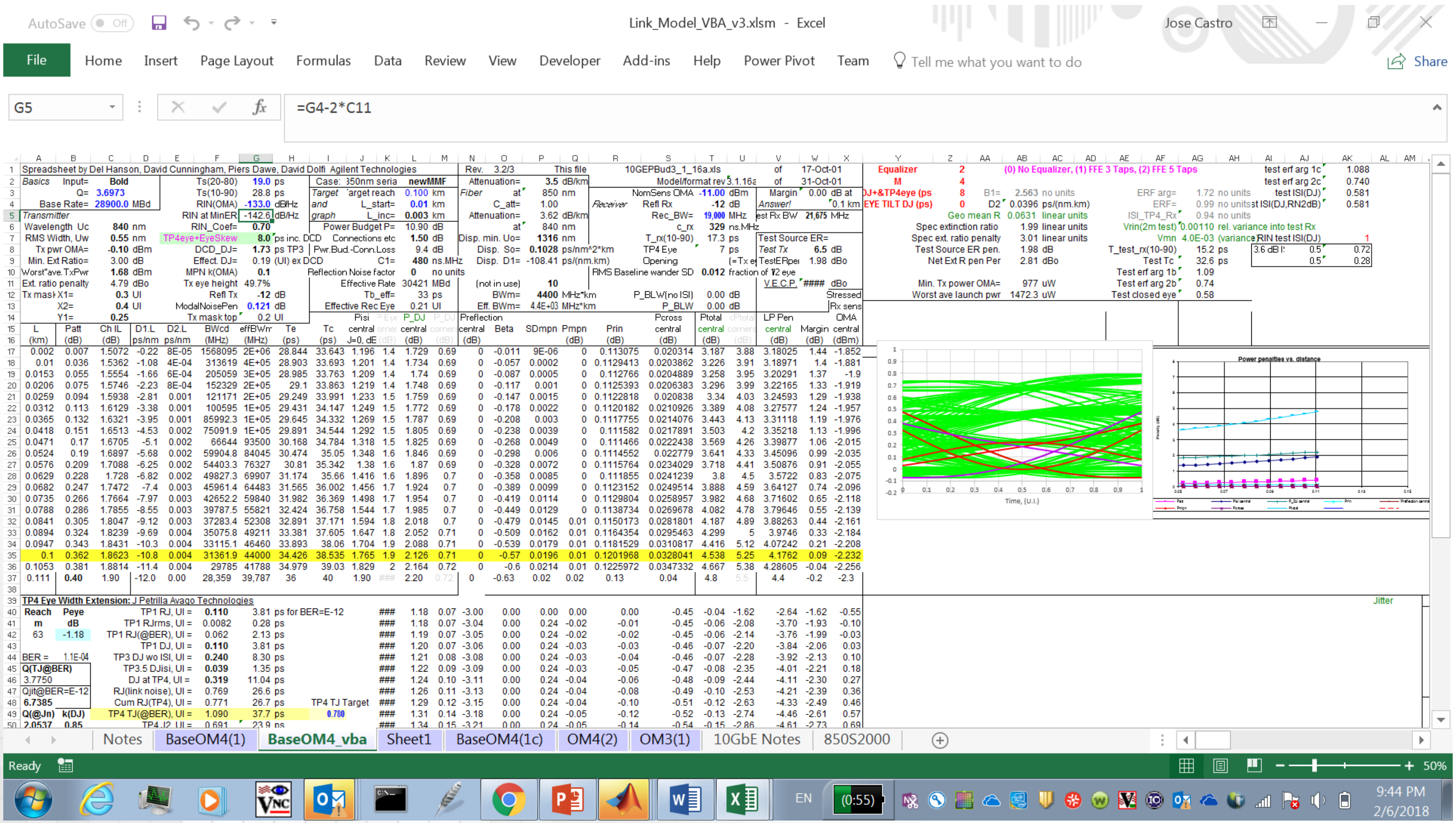
Examples

- To be shown during presentation



Examples

- To be shown during presentation



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