Link Model Spreadsheet for Optical PAM-4 Channels

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infrastructure for a connected world



Outline



Background

Backeround & Consecures

- 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

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- 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.



The Gaussian Channel



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

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.



$$E_{L}(J,T_{r},T_{p}) = h_{e}(0.5JT_{p},T_{r},T_{p}) - (M-1)[1 - h_{e}(0.5JT_{p},T_{r},T_{p})]$$

Power Penalty

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

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)

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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

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

- 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:

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

 $\frac{Power Penalty}{P_{ISI_{+}J} = 10log10(EEq(J,Tr,Tp))}$

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.

$$P_{ISI_{+}J} = 10\log 10(Eq(J + \left(\frac{\Delta T}{T_{p}}\right), Tr, Tp))$$





Noise Penalties (work in progress)

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

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



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)

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Link Model Spreadsheet

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Limitations of Link Model Spreadsheet



A significant portion of the worksheet is used for intermediary computations

Mostly Input parameters



Modified Spreadsheet



- 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)
   b_2 = 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)
   b_2 = 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

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 No equations in the results cells. VBA module updates results when an input is changed
 Two new Inputs for Equalization Type

and Signal Levels

												-											
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Examples



To be shown during presentation



Examples

PANDUIT

• To be shown during presentation

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A B C D E F C H 1 Spreadsheet by Del Hanson, David Cunningham, Piers Dawe, David Dotti Aglient 2 Base Input= Bold Ts(20-80) 19.0 ps Case: 53 3 0 - 3.6973 Ts(20-80) 19.0 ps Case: 53 4 Base Rate: 28900.0 MBd RIN(0MA)	J. K. L. M. N. O. P. O. R. S. T. U. V. W. X. Y. Z. AA. AB. AC. AD. A. At Technologies Rev. 3.2/3 This file 100EPBud3_1_6axis of 17-Oct-01 Equalizer 2 (I) No Equalizer, (I) FEE 3 fail Omm seria newMMM Attenuation= 3.5 dB/rm Model/formatrev/3.16s of 17-Oct-01 M 4 Ogen seria newMMM Attenuation= 3.5 dB/rm Model/formatrev/3.16s of 17-Oct-01 M 4 L_state 0.01 km F/Der at/ 85 on m NonSens DMA: -120 dB Margin / 0.00 dB J+47124 yet pis 8 B1= 2.563 no units L_state 0.01 km C.att 1.00 Rec.BV= 7.04 B Answer/ 0.1 km FVETILT DJ (ps) 0 D2/2 0.0396 ps/inm.km Lince 0.003 km Attenuation= 3.62 dB/rm Rec.BV= 7 ps Test Source ER= Spec exit.ratio penalty 3.01 linear units CrinLines 0.1038 ps/inm*2*km T p4/Eye 7 ps Test Source ER= 1.80 dB Test Source ER pen. 1.90 dB T_star Spec exit.ratio penalty 3.01 linear unit	AE AF AG AH AI AJ AK AL AM Am tpps, (2) FEE 5 Taps test ef arg 1c 1.088 test ef arg 2c 1.088 ERF arg 1.72 no units test 15(10,1) 0.581 test ef arg 1c 1.088 ISI, TP4, R* 0.94 no units to test Rx 0.94 no units to test Rx 1.581 1.091 Vm 4, 0E-03 (variance RIN test 15(10,1) 1 test arg 1c 0.57 0.72 Test Tc 32.6 ps 0.55 0.72 test arg 1c 0.28 est ef arg 1c 0.58 1.09 0.52 ps 0.55 0.28 est ef arg 2c 0.74 3.6 del !: 0.5 0.28
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3 TP4 Eve Width Extension: J Petril Avao: Technologies 8 Reach. Peye TP1 RJ, UI = 0.110 3.81 ps for BER=E-12 1 m dB TP1 RJ, UI = 0.0082 0.28 ps 2 63 -1.18 TP1 RJ, UI = 0.0082 0.28 ps 45 63 -1.18 TP1 RJ, UI = 0.0082 0.28 ps 45 64 TP1 RJ, UI = 0.010 3.81 ps 46 BER = -11E4M TP3 DJ wol SI, UI = 0.0240 8.30 ps 47 QINGBERI 0.319 13.5 ps 48 SC735 DJ wol SI, UI = 0.039 13.5 ps 49 GVI.000ERI DJ at TP4, UI = 0.039 13.6 ps 49 SC735 Cum RU(TP4), UI = 0.759 2.65 ps 40 SC MSW, M KUDJ TP4 TJ QIGEERI, UI = 0.759 2.75 ps TP4 TJ Jan 50 L4537 0.85 TP4 LD, UI = 0.691 2.33 ns MM 51 Z4537 0.85 Motes BaseOM4(1) BaseOM4_vb	### 1.18 0.07 3.00 0.00 0.00 0.00 -0.45 -0.04 -1.62 -2.64 -1.62 -0.55 ### 1.18 0.07 -3.00 0.00 0.24 -0.02 -0.45 -0.04 -1.62 -2.64 -1.62 -0.55 ### 1.19 0.07 -3.06 0.00 0.24 -0.02 -0.45 -0.06 -2.14 -3.76 -1.99 -0.03 ### 1.20 0.07 -3.06 0.00 0.24 -0.03 -0.04 -0.06 -0.44 -3.76 -1.99 -0.03 ### 1.20 0.07 -3.06 0.00 0.24 -0.03 -0.04 -0.07 -2.28 3.92 -2.13 0.10 ### 1.20 0.93 0.00 0.24 -0.03 -0.04 -0.07 -2.28 3.92 -2.13 0.10 ### 1.20 0.11 3.00 0.024 -0.04 -0.06 -0.04 -0.02 -0.47 -2.21 0.18 ### 1.26 0.11 3.	
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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

