# *Extending the Ethernet Link Model for EDC and Modulation Format*

Paul Voois

Norm Swenson

Tom Lindsay

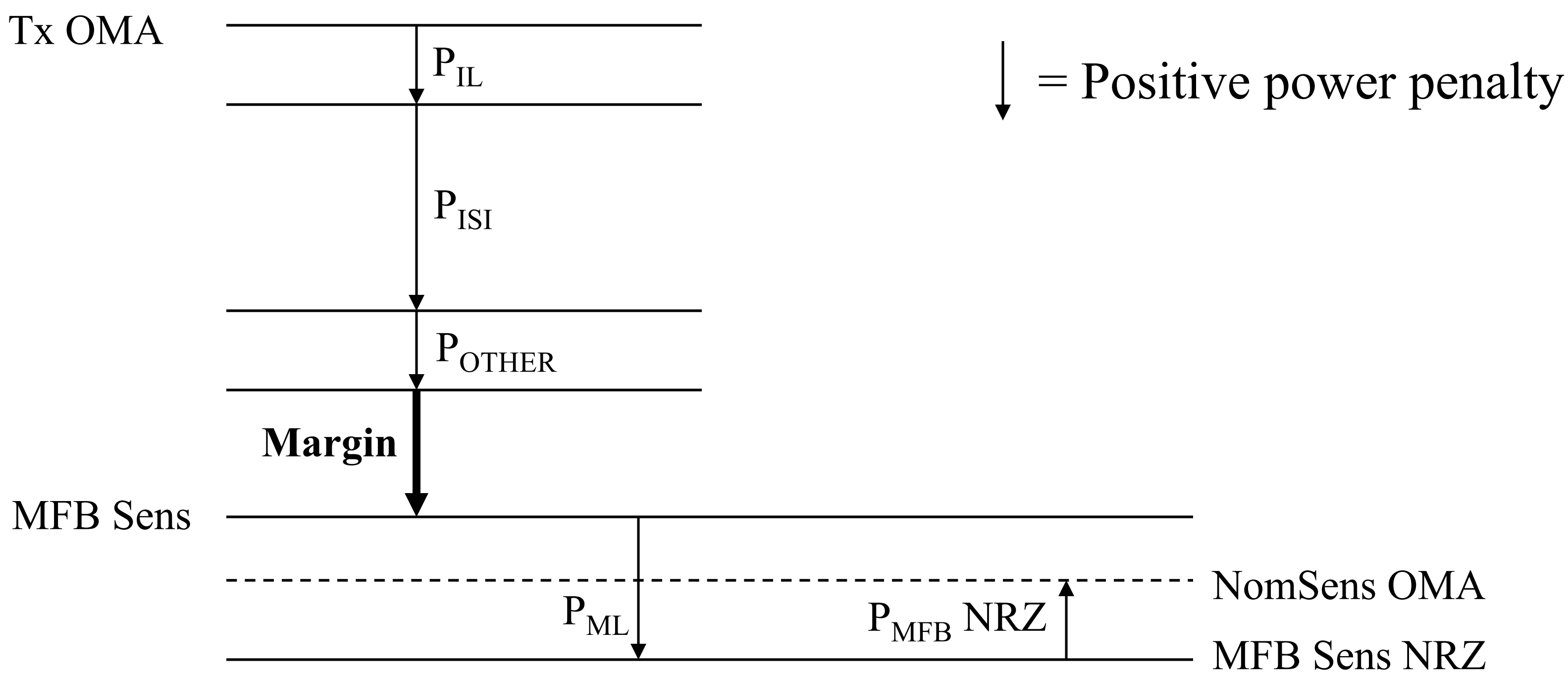
IEEE 802.3, Orlando FL

March 15-18, 2004

# *Overview*

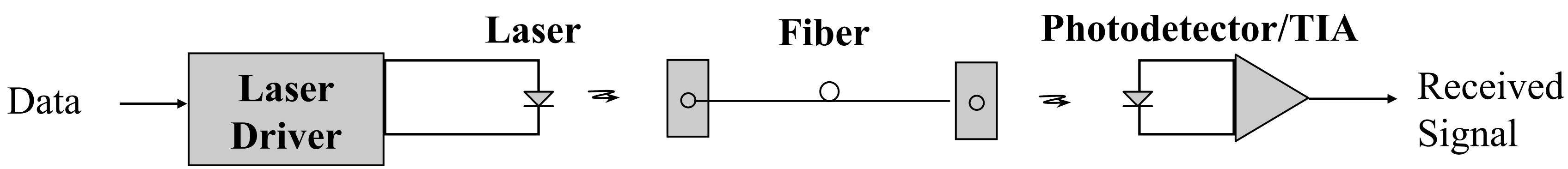
- Ethernet link model has been powerful tool for  development of past standards
- Should be extended for 10-Gbit/s FDDI MMF standard
- New elements include
  - EDC
  - Multilevel modulation

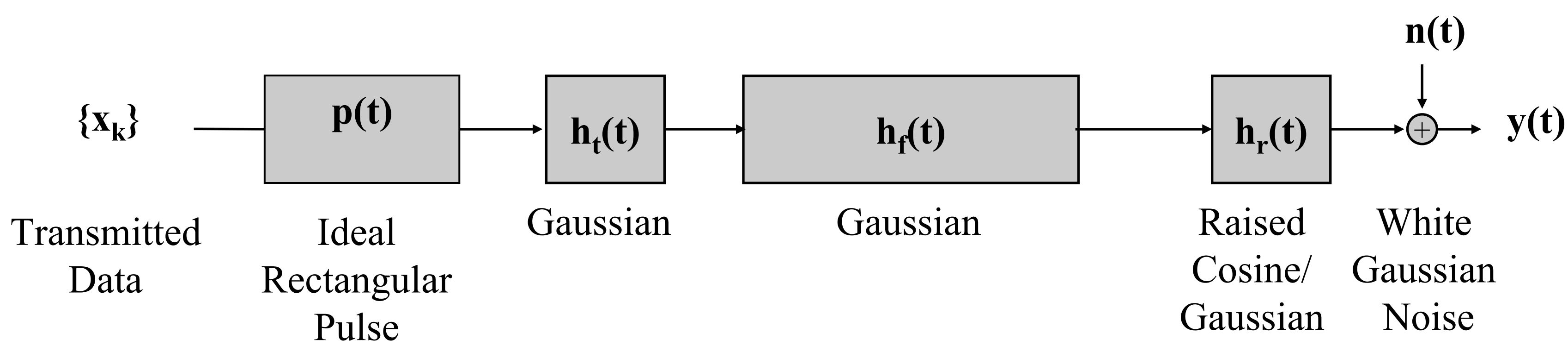
# *Link Budget*




- Nominal sensitivity is adjusted for
  - EDC: provides gain based on matched filter bound
  - Multilevel power penalty
- Result is "MFB Sensitivity" for margin calculation

# *Channel Model*



# *Channel Model*

- Transmitted Data
  - NRZ: $x_k$ Є {0, 1}, where Є = "is an element of the set"
  - Multilevel: $x_k$ Є {0, 1/(M-1), 2/(M-1), …, (M-2)/(M-1), 1}, where M is the number of levels. (M=2 for NRZ.)
- Transmit Pulse: Ideal rectangular pulse; width = 97 ps * $\log_2 M$
- Laser (same as 3.1.16a): Gaussian filter; specified by 20-80% rise time
- Fiber (same as 3.1.16a): Gaussian filter; BW = Modal BW / Length
- Optical Receiver (same as 3.1.16a): Gaussian filter; 3-dB BW related to RMS width according to raised cosine model. RMS width related to rise time according to Gaussian model.
- Noise: AWGN added to channel after optical receiver. Noise power spectral density determined by receiver sensitivity.

# *General Approach*

- Use Ethernet Link Model v3.1.16a, worksheet 1310S as starting point
- Modify $P_{ISI}$ to account for EDC (assume zero-forcing DFE)
- Add multilevel power penalty $P_{ML}$ to account for multilevel modulation
- Ignore RIN, MPN, Modal noise, jitter penalties for now; will incorporate in future versions of model
- Ignore nonideal equalizer effects (e.g. finite length, finite precision). Will incorporate in future versions.


ClariPhy Communications, Inc.

# MFB Sensitivity

- For power budget purposes, nominal OMA sensitivity is replaced by "Matched filter bound (MFB) sensitivity" $S_{MFB,M}$, which depends on the number of transmitted levels, M
  - $S_{MFB,M}$ is the OMA sensitivity of an ideal matched filter receiver on an ideal channel; i.e. one where the data modulated by a rectangular transmit pulse is transmitted without distortion
  - $S_{MFB,M}$ has a convenient mathematical relationship to $S_{ZFDFE}$, the sensitivity of a ZF-DFE receiver on an ISI channel
- $S_{MFB,NRZ}$, the MFB sensitivity for NRZ modulation, is related to nominal OMA sensitivity S by
  - $S_{MFB,\ NRZ} = P_{MFB,\ NRZ}\ S$, where
    - $P_{MFB,\ NRZ} = 1/(2\ B_n\ T)^{1/2}$
    - $B_n$ = optical receiver noise equivalent bandwidth (NEB), which is related to 3-dB electrical bandwidth by a constant
    - T = NRZ symbol period
    - $P_{MFB,\ NRZ}$ may be less than or greater than 1, depending on NEB

# *Multilevel Power Penalty*

- In the case of multilevel modulation with M levels, the MFB sensitivity is given by
  - $S_{MFB,\,M} = P_{ML}\, S_{MFB,\,NRZ}$, where $P_{ML}$ is the multilevel power penalty

$$P_{ml} = \frac{M-1}{\sqrt{\log_2 M}}$$

    - The factor of (M-1) comes from the fact that the spacing between levels is reduced by a factor of (M-1)
    - The factor of $(\log_2 M)^{1/2}$ comes from the fact that the symbol period is increased by a factor of $\log_2 M$; hence the SNR of the matched filter receiver increases by $(\log_2 M)^{1/2}$

# *ISI Penalty*

- The link model assumes an ideal zero-forcing DFE (ZF-DFE) receiver.
  - Infinite length, infinite precision equalizer
  - ISI penalty is independent of channel SNR, which makes spreadsheet implementation much easier
    - This is not true for MMSE-DFE, where ISI penalty will vary with SNR for the same channel impulse response
  - Performance should nearly equal MMSE-DFE for "low" ISI penalties ("low" not quantified here - needs further analysis); however, performance will be significantly worse than MMSE-DFE for "high" ISI penalties
- $P_{ISI} = S_{ZFDFE}/S_{MFB,M}$

# *Calculation of ISI Penalty (ZF-DFE Case)*

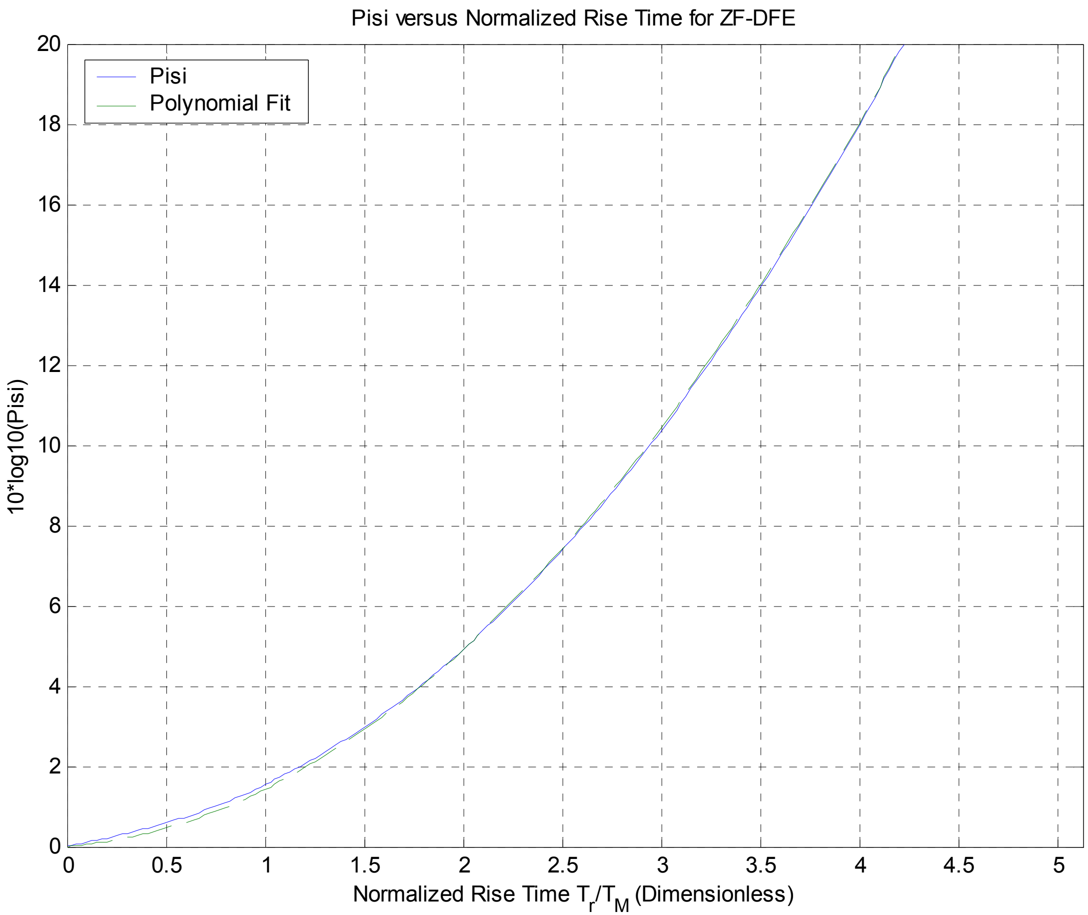
$$P_{isi}(\tau') = \exp\left\{-\frac{1}{2}\int_0^1 \ln\left[\sum_k \mathrm{sinc}^2(f+k)e^{-4(\pi\tau'(f+k))^2}\right]df\right\}$$

- $\tau' = \tau_c/T_M$, where $\tau_c$ is the RMS width of the aggregate (laser/fiber/optical receiver) gaussian channel and $T_M$ is the symbol period for M-level modulation
- The link model uses normalized rise time instead of normalized standard deviation:
  - $T_c' = T_c / T_M$, where $T_c$ is the 10-90% rise time of the aggregate gaussian channel
  - $T_c' = 2.5630\,\tau'$
- $10\log_{10}P_{isi}(T_c')$ may be reasonably approximated over a range of $T_c'$ by a parabola (see following plot)
  - $10\log_{10}P_{ISI}(T_c') \sim A_1 T_c' + A_2 (T_c')^2$



ClariPhy Communications, Inc.

# *Approximation of ISI Penalty*




- $A_1 = 0.396$
- $A_2 = 1.029$
- Polynomial fit is accurate to within 0.130 dB over the shown range

# *Excel Spreadsheet*

- Naming conventions for worksheet: “MOD_XX”
  - MOD specifies modulation scheme (NRZ, PAM4)
  - XX specifies nominal optics speed (10 = 10G; LS = lowspeed)
  - Cases currently covered: NRZ_10, PAM4_10, NRZ_LS, PAM4_LS
  - NRZ_LS, PAM4_LS use nominal 4G specs
- Color coding (in order of priority)
  - Blue denotes values that vary among the worksheets
  - Green denotes values that have changed from v3.1.16a sheet 1310S
  - Red denotes new cells versus v3.1.16a

# *Link Budget Relationships*

- Sensitivity
  - S = nominal OMA sensitivity
  - $S_{MFB,NRZ} = S + P_{MFB,NRZ}$
  - $S_{MFB,M} = S_{MFB,NRZ} + P_{ML}$
- Power budget
  - $PB = TxOMA - S_{MFB,M}$
- Total power penalty
  - $P_{total} = P_{att} + P_{ISI}$
- Margin
  - $Margin = PB - CL - P_{total}$
    - CL = connector loss
- (Penalties in dB form)

# *Parameter Input Section*

Spreadsheet by Del Hanson, David Cunningham, Piers Dawe, David Dolfi Agilent Technologies
Modified for 10G FDDI MMF by Paul Voois ClariPhy Communications

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Rev. NA | | This file | NA | |
| | | | | | | | | | Attenuation= | 1.5 | dB/km | Model/format rev | |
| *Basics* Input= | **Bold** | | Ts(20-80) | **90** | ps | Case: 1310nm serial | **MMF** | | *Fiber* at | 1310 | nm | NomSens OMA | **-17.00** |
| Q= | **7.04** | | Ts(10-90) | 137 | ps | *Target* Target reach | **0.30** | km | C_att= | 1.01 | | Pmfb NRZ | 1.108 |
| Base Rate= | **5156.25** | MBd | RIN(OMA) | **-130** | dB/Hz | *and* L_start= | **0.1** | km | Attenuation= | 1.56 | dB/km | MFB Sens NRZ | -15.89 |
| *Transmitter* | | | RIN at MinER | -137.3 | dB/Hz | *graph* L_inc= | **0.01** | km | at | 1269 | nm | MFB Sens | -12.63 |
| Wavelength Uc | **1269** | nm | RIN_Coef= | **0.70** | | Power Budget P= | 9.43 | dB | Disp. min. Uo= | **1365** | nm | *Receiver* Refl Rx | **-12** |
| Uw (see notes) | **0.62** | nm | Det.Jitter | **6.0** | ps inc. DCD | Connections C | **2** | dB | Disp. So= | **0.093** | ps/nm^2*km | Rec_BW= | **3,000** |
| Tx pwr OMA= | **-3.20** | dBm | DCD_DJ= | **6** | ps TP3 | Pwr.Bud.-Conn.Loss | 7.426 | dB | Disp. D1= | -9.99 | ps/(nm.km) | NEB Factor | 1.032 |
| Min. Ext Ratio= | 4.00 | dB | Effect. DJ= | 0.00 | (UI) ex DCD | C1= | **480** | ns.MHz | | | | NEB | 3096 |
| "Worst"ave.TxPwr | **-2.55** | dBm | MPN k(OMA) | **0** | | Reflection Noise factor | **0.6** | no units | (not in use) | **10** | | c_rx | **329** |
| Ext. ratio penalty | 3.66 | dBo | Tx eye height | #NAME? | | Effective Rate | 5321 | MBd | BWm= | **5E+02** | MHz*km | T_rx(10-90) | 109.7 |
| Tx mask X1= | **0.3** | UI | Refl Tx | **-12** | dB | Tb_eff= | 188 | ps | Eff. BWm= | 5.0E+02 | MHz*km | TP4 Ey | 39 |
| X2= | **0.4** | UI | ModalNoisePen | **0** | dB | Effective Rec Eye | 0.21 | UI | | | | Opening | |
| Y1= | **0.25** | | Tx mask top | 0.2 | UI | Pisi Constant A1 | 0.396 | no units | | | | RMS Baseline wander SD | **0.025** |
| Num Tx Levels | **4** | | Sym Period Tb | 193.9 | ps | Pisi Constant A2 | 1.029 | no units | | | | P_BLW(no ISI) | 0.07 |
| Multilevel Pen | 3.27 | dB | | | | | | | | | | P_BLW | ##### |

(From PAM4_LS worksheet)

# *Margin Calculation Section*

| L (km) | Patt (dB) | Ch IL (dB) | D1.L ps/nm | D2.L ps/nm | BWcd (MHz) | effBWm (MHz) | Te (ps) | Tc (ps) | Norm Tc no units | Pisi central J=0, dB | Margin (dB) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.002 | 0.00 | 2.00 | -0.02 | 0.00 | 2E+07 | 2.5E+05 | 137 | 175 | 0.90 | 1.20 | 6.2 |
| **0.10** | **0.16** | **2.16** | **-1.0** | **0.00** | **301,817** | **5,000** | **167** | **200** | 1.03 | 1.50 | **5.8** |
| 0.11 | 0.17 | 2.17 | -1.1 | 0.00 | 274,379 | 4,545 | 173 | 205 | 1.05 | 1.56 | 5.7 |
| 0.12 | 0.19 | 2.19 | -1.2 | 0.00 | 251,514 | 4,167 | 179 | 210 | 1.08 | 1.63 | 5.6 |
| 0.13 | 0.20 | 2.20 | -1.3 | 0.01 | 232,167 | 3,846 | 185 | 215 | 1.11 | 1.71 | 5.5 |
| 0.14 | 0.22 | 2.22 | -1.4 | 0.01 | 215,583 | 3,571 | 192 | 221 | 1.14 | 1.79 | 5.4 |
| **0.15** | **0.23** | **2.23** | **-1.5** | **0.01** | **201,211** | **3,333** | **199** | **227** | 1.17 | 1.87 | **5.3** |
| 0.16 | 0.25 | 2.25 | -1.6 | 0.01 | 188,635 | 3,125 | 206 | 233 | 1.20 | 1.96 | 5.2 |
| 0.17 | 0.27 | 2.27 | -1.7 | 0.01 | 177,539 | 2,941 | 213 | 239 | 1.23 | 2.06 | 5.1 |
| 0.18 | 0.28 | 2.28 | -1.8 | 0.01 | 167,676 | 2,778 | 220 | 246 | 1.27 | 2.16 | 5.0 |
| 0.19 | 0.30 | 2.30 | -1.9 | 0.01 | 158,851 | 2,632 | 228 | 253 | 1.30 | 2.27 | 4.9 |
| **0.20** | **0.31** | **2.31** | **-2.0** | **0.01** | **150,908** | **2,500** | **236** | **260** | 1.34 | 2.38 | **4.7** |
| 0.21 | 0.33 | 2.33 | -2.1 | 0.01 | 143,722 | 2,381 | 244 | 267 | 1.38 | 2.50 | 4.6 |
| 0.22 | 0.34 | 2.34 | -2.2 | 0.01 | 137,189 | 2,273 | 252 | 274 | 1.42 | 2.62 | 4.5 |
| 0.23 | 0.36 | 2.36 | -2.3 | 0.01 | 131,225 | 2,174 | 260 | 282 | 1.45 | 2.75 | 4.3 |
| 0.24 | 0.37 | 2.37 | -2.4 | 0.01 | 125,757 | 2,083 | 268 | 289 | 1.49 | 2.88 | 4.2 |
| **0.25** | **0.39** | **2.39** | **-2.5** | **0.01** | **120,727** | **2,000** | **276** | **297** | 1.53 | 3.02 | **4.0** |
| 0.26 | 0.41 | 2.41 | -2.6 | 0.01 | 116,083 | 1,923 | 285 | 305 | 1.57 | 3.17 | 3.9 |
| 0.27 | 0.42 | 2.42 | -2.7 | 0.01 | 111,784 | 1,852 | 293 | 313 | 1.61 | 3.32 | 3.7 |
| 0.28 | 0.44 | 2.44 | -2.8 | 0.01 | 107,792 | 1,786 | 302 | 321 | 1.65 | 3.47 | 3.5 |
| 0.29 | 0.45 | 2.45 | -2.9 | 0.01 | 104,075 | 1,724 | 310 | 329 | 1.70 | 3.63 | 3.3 |
| **0.30** | **0.47** | **2.47** | **-3.0** | **0.01** | **100,606** | **1,667** | **319** | **337** | 1.74 | 3.80 | **3.2** |

(From PAM4_LS worksheet. Blank columns hidden)

# *Summary of Results*

| Length (km) | NRZ_10 | | NRZ_LS | | PAM4_10 | | PAM4_LS | |
|---|---|---|---|---|---|---|---|---|
| | Pisi (dB) | Margin (dB) | Pisi (dB) | Margin (dB) | Pisi (dB) | Margin (dB) | Pisi (dB) | Margin (dB) |
| 0.002 | 1.1 | 7.2 | 4.1 | 6.6 | 0.4 | 4.7 | 1.2 | 6.2 |
| 0.100 | 2.3 | 5.9 | 5.2 | 5.4 | 0.7 | 4.2 | 1.5 | 5.8 |
| 0.150 | 3.7 | 4.4 | 6.6 | 3.9 | 1.1 | 3.7 | 1.9 | 5.3 |
| 0.200 | 5.6 | 2.4 | 8.5 | 1.9 | 1.6 | 3.1 | 2.4 | 4.7 |
| 0.250 | 8.1 | -0.2 | 10.9 | -0.6 | 2.3 | 2.4 | 3.0 | 4.0 |
| 0.300 | 11.1 | -3.2 | 13.8 | -3.6 | 3.1 | 1.5 | 3.8 | 3.2 |

- For a given distance, PAM4 has significantly lower $P_{ISI}$ than NRZ
  - Partially offset by multilevel penalty
- Incorporation of additional penalties will reduce margin
  - EDC implementation penalty, RIN, modal noise, jitter, etc.