Incorporating RIN into the Ethernet Link Model for EDC

Version 4

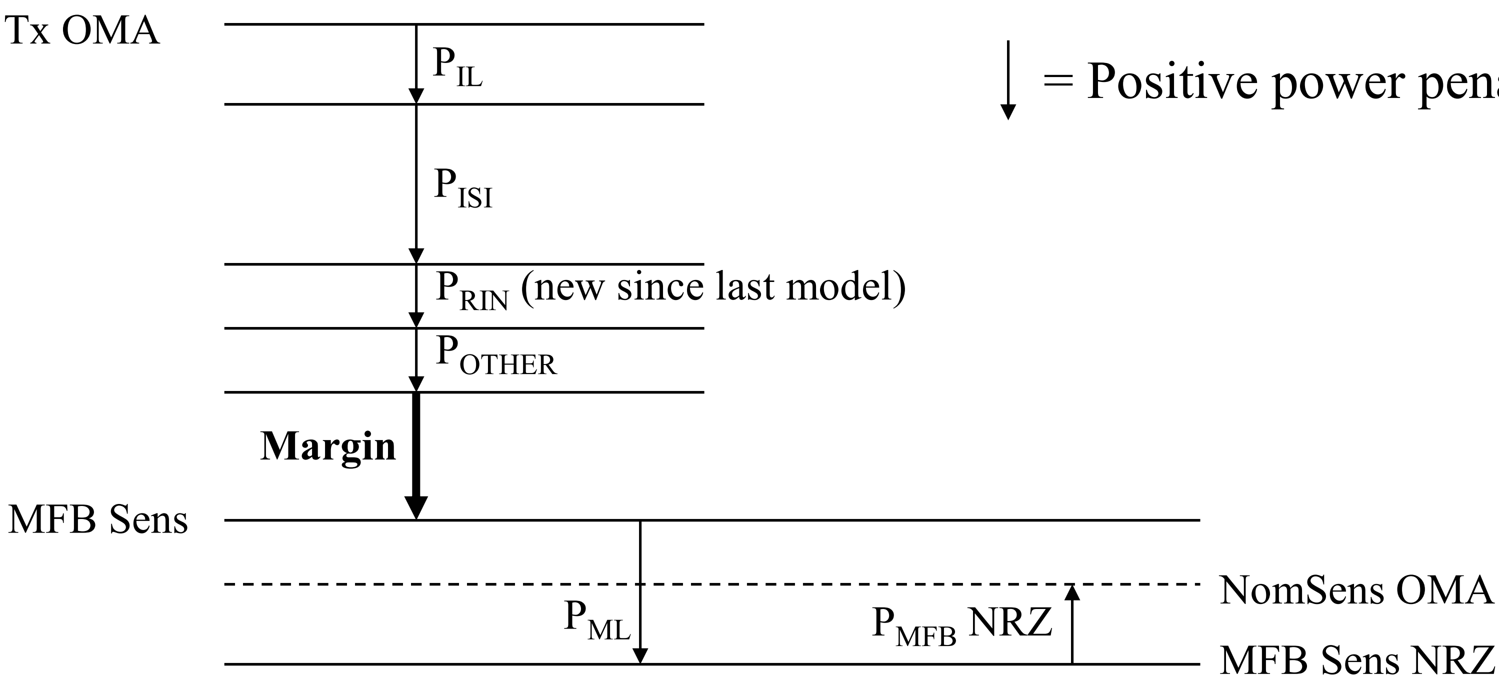
Paul Voois
Norm Swenson

IEEE 802.3, Long Beach CA
May 24-27, 2004

Overview

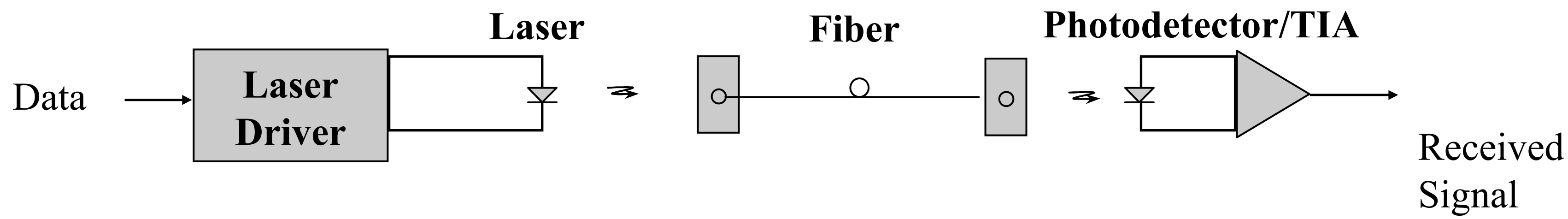
- In Orlando (March 2004) we presented an Ethernet link model that accounts for both EDC and multilevel modulation
  - Presentation: http://www.ieee802.org/3/10GMMFSG/public/mar04/voois_1_0304.pdf
  - Excel Spreadsheet: http://www.ieee802.org/3/10GMMFSG/public/mar04/voois_2_0304.xls
- Today's presentation describes the incorporation of RIN penalty into the link model
- An updated Excel spreadsheet is available

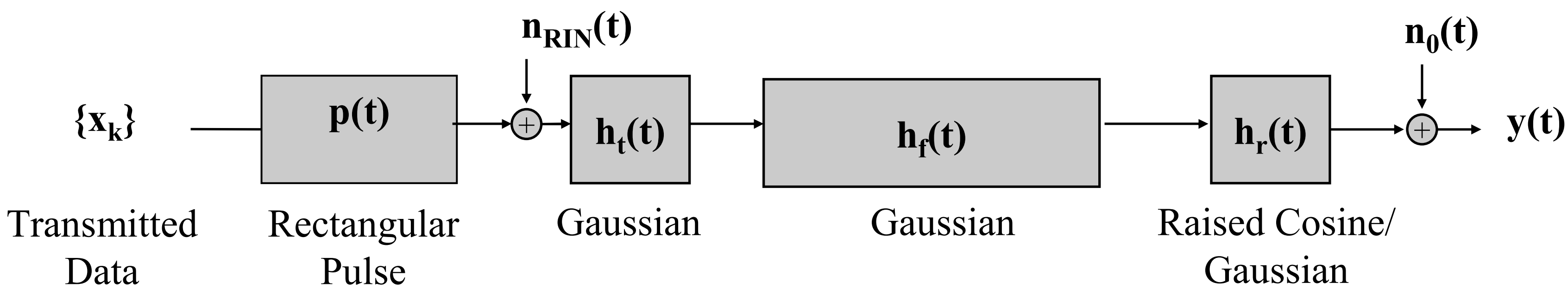
Link Budget



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

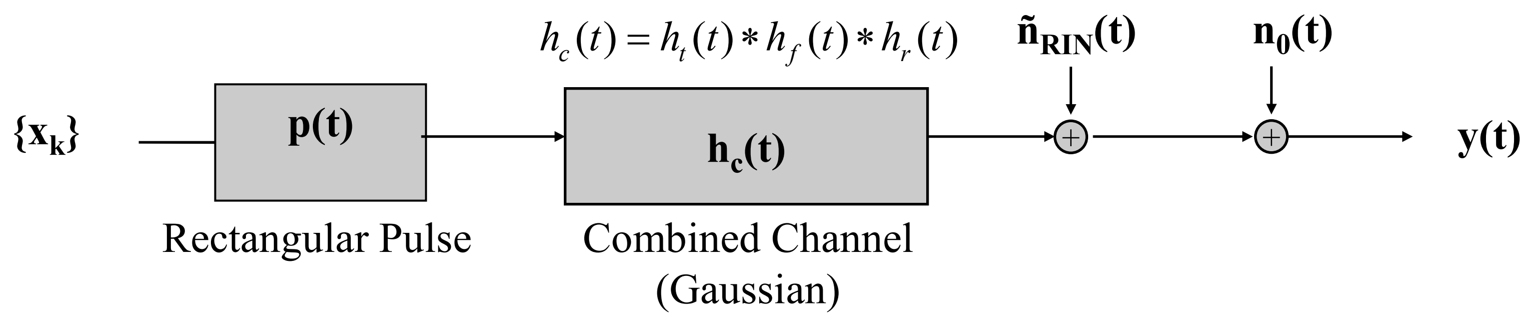
Channel Model





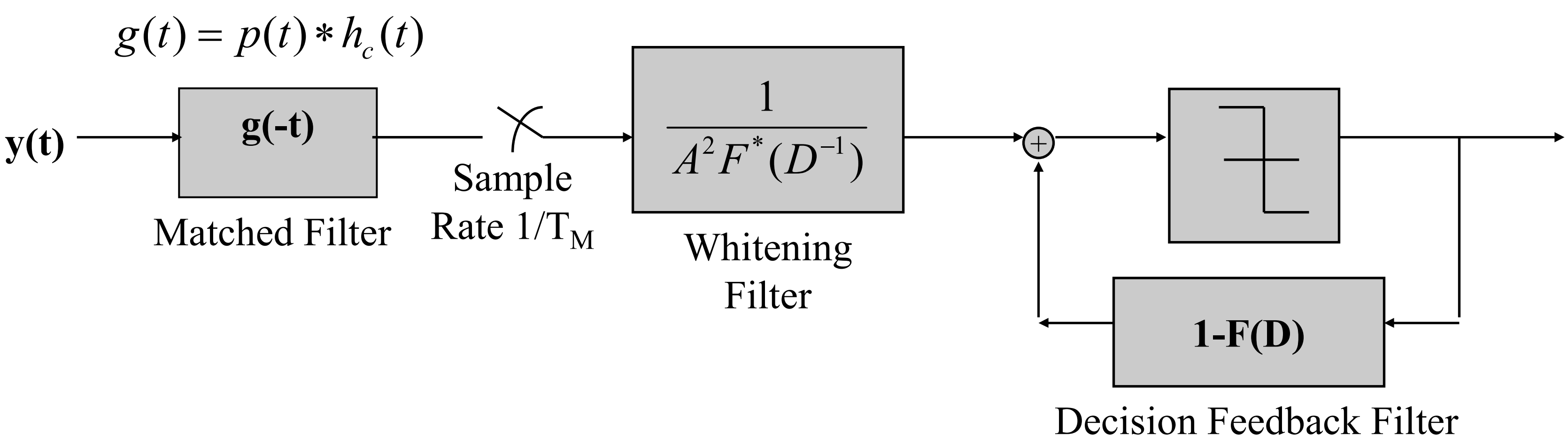
- $n_{RIN}(t)$ – Laser relative intensity noise (new since last model)
  - Assumed stationary (ignores variation in noise power with modulation)
  - Assumed white, Gaussian: 2-sided power spectral density (PSD) = $N_{RIN}/2$
  - N_{RIN} proportional to average power squared
- $n_0(t)$ – Receiver noise
  - Assumed white, Gaussian: 2-sided PSD = $N_0/2$

Equivalent White Noise Channel Model



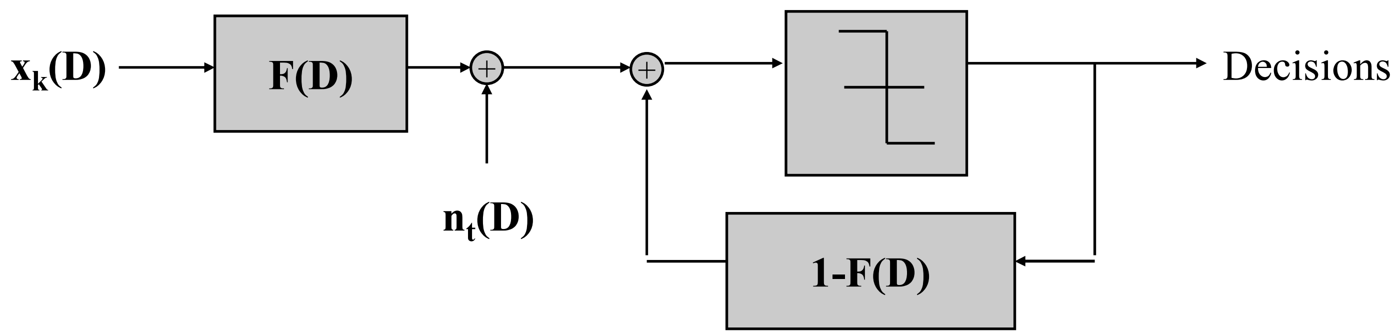
- Refer RIN to the channel output: $\tilde{n}_{RIN}(t)$ has PSD = $(N_{RIN}/2)\ H_c(f)^2$
- <u>Assume</u> a ZF-DFE designed for a white noise channel
  - Suboptimal, but a reasonable assumption if RIN power is small compared to receiver noise power. In this case, total noise is nearly white.
  - Significantly simplifies the spreadsheet implementation: P_{ISI} depends on the channel only, not noise
- <u>Approximate</u> $\tilde{n}_{RIN}(t)$ as white noise with PSD = $\tilde{N}_{RIN}/2$, where $\tilde{N}_{RIN}$ is chosen such that the RIN variance at the ZF-DFE decision element is the same as it is for the true (non-white) noise

Zero Forcing DFE Architecture



ClariPhy Communications, Inc.

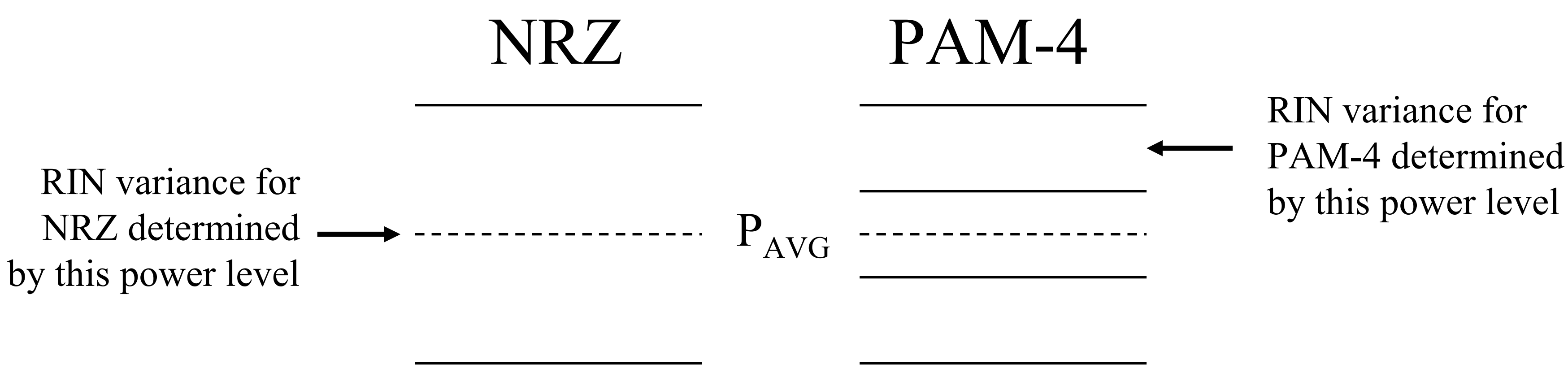
ZFDFE Equivalent Discrete-Time Channel



- All sequences shown in D-transform notation
- F(D) causal, monic: $1 + f_1 D + f_2 D^2 + \ldots$
- $n_t(D)$ is total noise (RIN + receiver) with variance σ_t^2

ClariPhy Communications, Inc.

Multilevel RIN Adjustment



- RIN variance determined by "average power"
  - NRZ case: use actual average power
  - PAM-M case: use halfway point between highest two levels, under the assumption that BER is dominated by the errors between these two levels
- Define multilevel RIN adjustment as the ratio between the "average power" used for PAM-M and that used for NRZ (E = extinction ratio):

$$P_{\text{ML-RIN}} = \frac{(2M-3)E+1}{(M-1)(E+1)} = \frac{5E+1}{3(E+1)} \text{ for PAM-4}$$

ClariPhy Communications, Inc.

Scaling

- For convenience, we scale both signal and noise amplitude so that the total noise variance at the ZF-DFE decision element is

$$\hat{\sigma}_t^{\,2} = \frac{1}{Q_0^{\,2}}$$

  - Similar approach used in original 10GE link model
  - Simplifies noise penalty calculations
  - Does not affect penalty values

RIN Penalty

- The RIN penalty is given by (linear scale)

$$P_{\mathrm{RIN}} = \frac{\hat{\sigma}_t}{\sqrt{\hat{\sigma}_t^2 - \hat{\sigma}_{\mathrm{RIN}}^2}} = \frac{1}{\sqrt{1 - Q_0^2 \hat{\sigma}_{\mathrm{RIN}}^2}}$$

- Where the (scaled) RIN variance is (all terms in linear scale)

$$\hat{\sigma}_{\mathrm{RIN}}^2 = \alpha_{\mathrm{RIN}} P_{\mathrm{ISI}}^2 \frac{RIN_{\mathrm{OMA}}}{2T_M} P_{\mathrm{ML-RIN}}^2 (M-1)^2$$

ClariPhy Communications, Inc.

RIN Penalty - Detail

- α_{RIN} is defined as the ratio of the referred RIN PSD to the actual RIN PSD:

$$\alpha_{\mathrm{RIN}}(\tau_c') = \frac{\widetilde{N}_{\mathrm{RIN}}}{N_{\mathrm{RIN}}} = \int_0^1 \frac{\sum_k \mathrm{sinc}^2(f+k)e^{-8\left(\pi\tau_c'(f+k)\right)^2}}{\sum_k \mathrm{sinc}^2(f+k)e^{-4\left(\pi\tau_c'(f+k)\right)^2}} df$$

- P_{ISI} is given by

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

- $\tau_c' = \tau_c/T_M$, where τ_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

ClariPhy Communications, Inc.

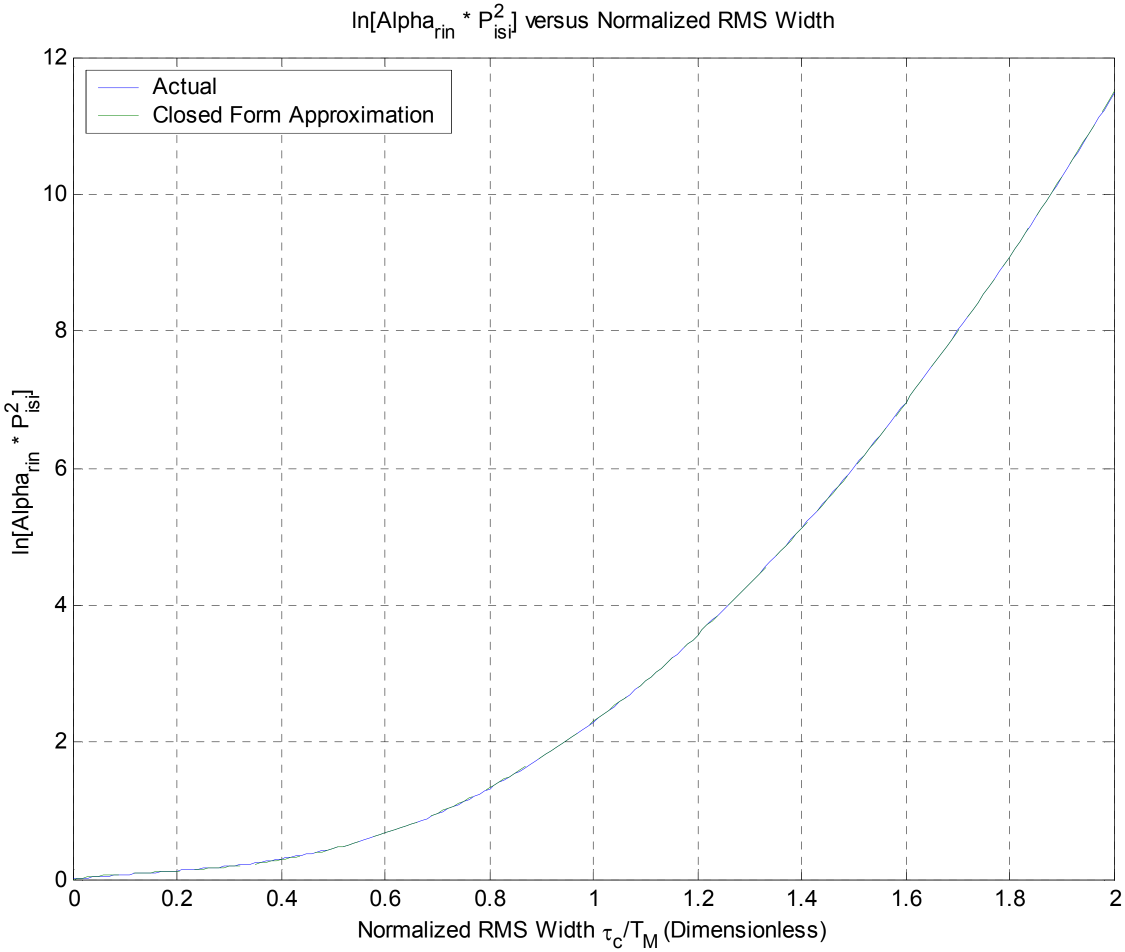
RIN Formula – Closed Form Approximation

- In order to compute the RIN penalty in Excel, we use the closed-form approximation

$$\lambda(\tau_c') = \ln\left(\alpha_{\mathrm{RIN}}(\tau_c')P_{\mathrm{ISI}}{}^2(\tau_c')\right) \approx A_0\tau_c' e^{-3.5\tau_c'} + A_1\tau_c' + A_2\tau_c'^2$$

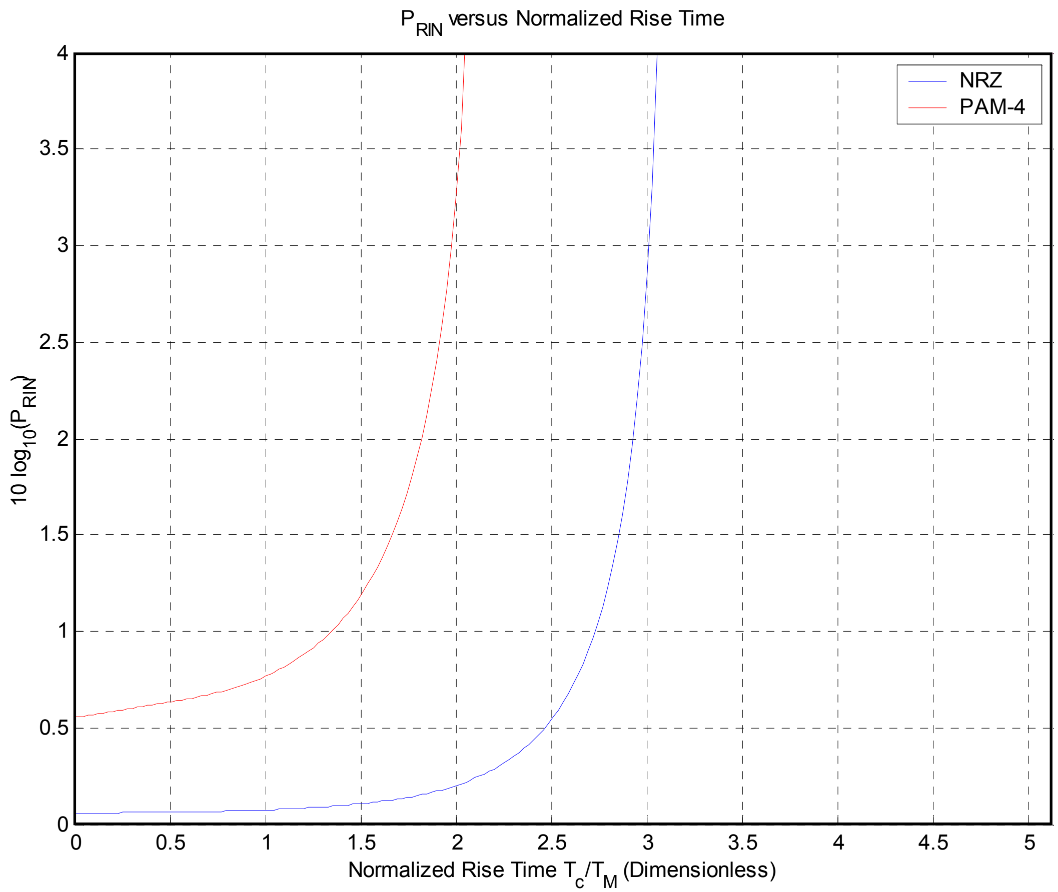
- Constants determined by least-squared error fit over τ_c' in the range [0,2]:
  - $A_0 = 2.4073$, $A_1 = -1.2928$, $A_2 = 3.5211$
- The following plot shows the actual versus approximate value of $\lambda(\tau_c')$ over this range
- The spreadsheet actually computes λ based on normalized rise time $T_c' = T_c/T_M$, where $T_c' = 2.5630\ \tau_c'$

Closed Form Approximation



ClariPhy Communications, Inc.

Example



- RIN Penalty (dB scale) vs. normalized 10-90% rise time T_c'
  - Higher T_c' means more ISI
  - For a given channel, T_c' is twice as large for NRZ as for PAM-4
- Parameters
  - RIN_{OMA} = -130 dB/Hz
  - ER = 6 dB
  - Standard 10G specs on laser, receiver

Comparison to Previous Ethernet Link Model

- Previous 10GE Link Model assumed a slicer (not EDC) receiver and used the following formula for RIN variance:

$$\hat{\sigma}^2_{\mathrm{RIN,Slicer}} = k_{\mathrm{RIN}} P^2_{\mathrm{ISI,Slicer}} RIN_{\mathrm{OMA}} BW_{\mathrm{eff}}$$

- Comparison to the formula presented here shows that EDC reduces RIN variance by the ratio

$$\frac{\hat{\sigma}^2_{\mathrm{RIN,Slicer}}}{\hat{\sigma}^2_{\mathrm{RIN}}} = k_{\mathrm{RIN}} \left(\frac{2BW_{\mathrm{eff}} T_M}{\alpha_{\mathrm{RIN}}} \right) \frac{P^2_{\mathrm{ISI,Slicer}}}{P^2_{\mathrm{ISI}}} \frac{1}{(M-1)^2 P^2_{\mathrm{ML-RIN}}}$$

Fudge factor (0.7)

Difference in noise variance between slicer and EDC Rx

P_{ISI} Lower for EDC

Multilevel Effect

Comparison to Previous Analysis of PAM-M

- Previous analysis of RIN for multilevel modulation showed significant penalty for PAM-M versus NRZ
  - http://www.ieee802.org/3/10G_study/public/july99/cunningham_1_0799.pdf
- This analysis did not account for
  - ISI (P_{ISI})
  - Reduction in bandwidth based on increased symbol period (T_M)
- Both these effect reduce the PAM-4 penalty with respect to NRZ

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

Interesting Results

- Using link budget specs from dawe_1_0504 with NRZ
  - RIN_{OMA} = -128 dB/Hz
  - P_{ISI} = 5.22 dB ➔ P_{RIN} = 0.37 dB (Good agreement)
  - Margin ~ 0 dB at 220m
    - Gaussian model, ZFDFE are conservative, so 220m should be OK
- Using Tx OMA and RIN_{OMA} from dawe_1_0504, but 4G laser and receiver specs with PAM-4
  - RIN_{OMA} = -128 dB/Hz
  - Margin ~ 0 dB at 270m
  - Margin ~ 1.6 dB at 220m
  - Performance sensitive to extinction ratio (used 4 dB)