PAM MPI – Overview & Recommendations

Next Generation 40Gb/s and 100Gb/s Optical Ethernet Study Group

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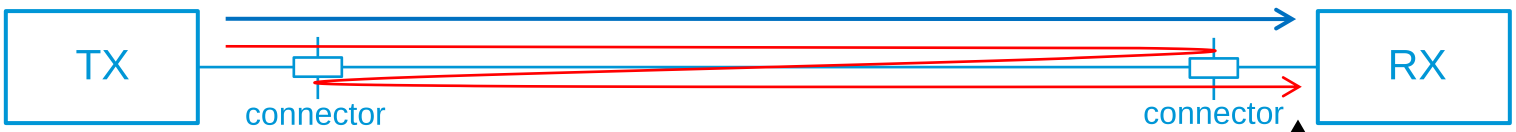
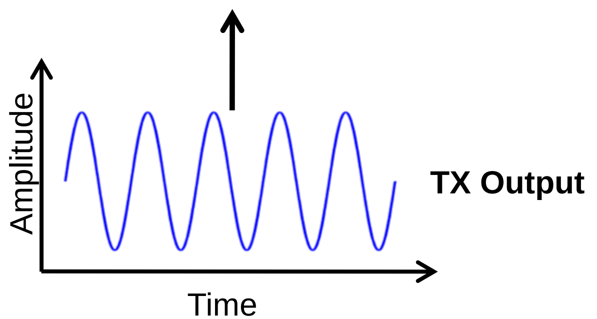
Outline

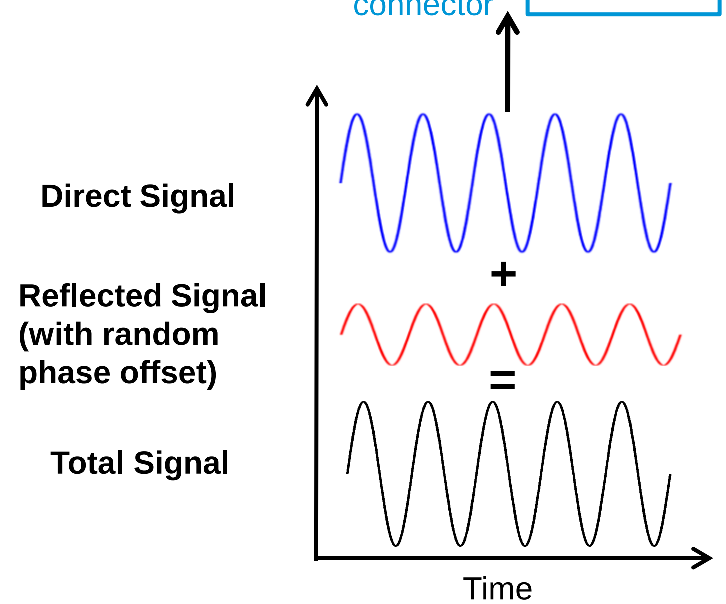
- Concept (Problem Statement)
- Analysis & Simulation
- Link Configuration
- Conclusion

Concept -- Interfering Optical Signals

- Each pair of connectors in the link causes a reflection that combines with the intended signal. Rx receives the sum.



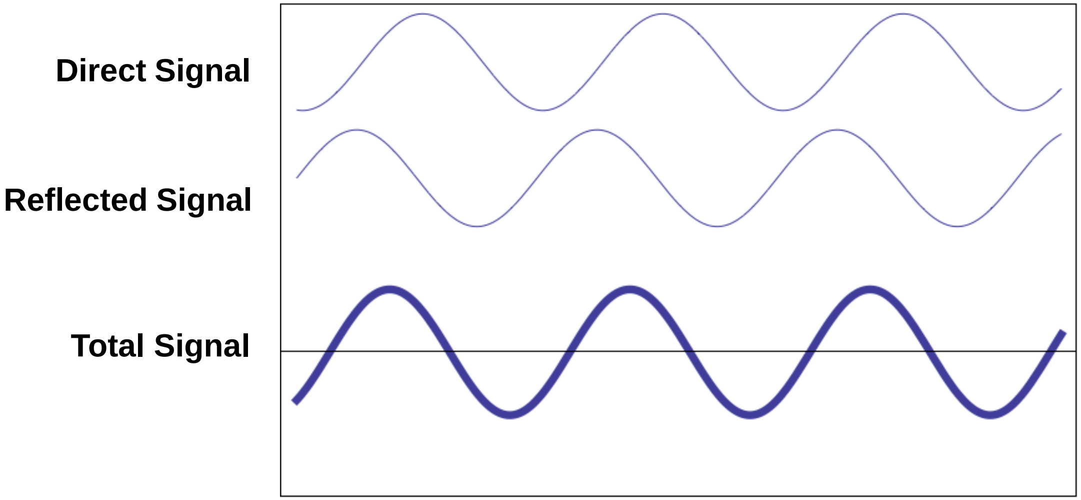




- The amplitude of the total signal depends on the phase difference between the direct and reflected signals

Effect on Amplitude of Total Signal

- Addition of two signals of same frequency (animation, turn on Slide Show mode):



- Since the frequencies are the same, the phase difference determines the resulting total amplitude.
- In practice, laser phase noise / spectral width, multiple connectors lead to random noise at receiver. We call it “Link RIN”.

Link with Multiple Connectors

- The simple case described earlier can be extended to consider attenuation and multiple connectors.
- Key variables that affect performance and choice of link configuration are:
  - Laser linewidth
  - Number of connectors
  - Return loss (of connectors and of MDI interface)
  - Number of PAM levels
  - Fiber attenuation and connector loss

Analysis: Various Approaches

- There are 3 main themes in these approaches:

    1. Frequency-domain analysis, modeling MPI as Link RIN. [1], [6]
    2. Time-domain mixing, looking at MPI statistics.[2], [4], [5]
    3. Upper-bound approach, looking only at bounds of MPI process.[3]

- The following is a brief overview of each approach.

Frequency Domain, Link RIN approach

- Ref [1] analyzes MPI with frequency-domain tools, analogous to RIN(f).
- Calculates power spectral density of MPI
  - Computed by taking the Fourier transform of the autocorrelation of the time-domain noise term.
  - Power spectrum is Lorentzian.
- Used in the same way as a usual RIN value.
- Takes account of path length, phase noise, and other key variables.
- Ref [6] extended it to lower values of reflectance.

Frequency Domain, Link RIN approach

- Link RIN spectral power density is calculated by formula (15) in Ref. [1],

$$RIN(f) = \frac{4}{\pi}\left[\frac{\Delta\nu}{f^2 + (\Delta\nu)^2}\right] \cdot \frac{N(N-1)}{2} \cdot R_c^{\ 2} \qquad\qquad 2\pi\Delta\nu\tau >> 1$$

where R_c is an effective reflection coefficient of the link connections (assumed polarization axis of the two fields are the same as the worst case condition), $\Delta\nu$ is a spectral width of the laser and τ is a round-trip path (reflection) delay time and N is a number of connection points.
This condition is assumed as a phase difference between direct and each double reflected signal is under the worst case (90 deg) conditions.

Frequency Domain, Link RIN approach

- Bit Error Ratio is calculated with assumption of Gaussian distributed pdf with only adjacent symbols,

$$BER = \frac{1}{\log_2(M)} \cdot \frac{M-1}{M} \cdot erfc\left(\frac{Q}{\sqrt{2}}\right)$$

where $$Q = \frac{1}{M} \cdot \left(\frac{I_{M-1} - I_{M-2}}{\sigma_{M-1} + \sigma_{M-2}} + \frac{I_{M-2} - I_{M-3}}{\sigma_{M-2} + \sigma_{M-3}} + \cdots + \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \right)$$

Noise terms used can be written as follows;

Thermal noise:

$$\sigma_T{}^2 = N_{th}{}^2 \Delta f$$

Shot noise:

$$\sigma_S{}^2 = 2qI_m \Delta f$$

Source RIN noise:

$$\sigma_{S-RIN}{}^2 = RIN \cdot I_m{}^2 \Delta f$$

Link RIN noise:

$$\sigma_{L-RIN}{}^2 = \frac{1}{M} \cdot RIN \cdot \left(I_{M-1}{}^2 + I_{M-2}{}^2 + \cdots + I_0{}^2\right)\Delta f$$

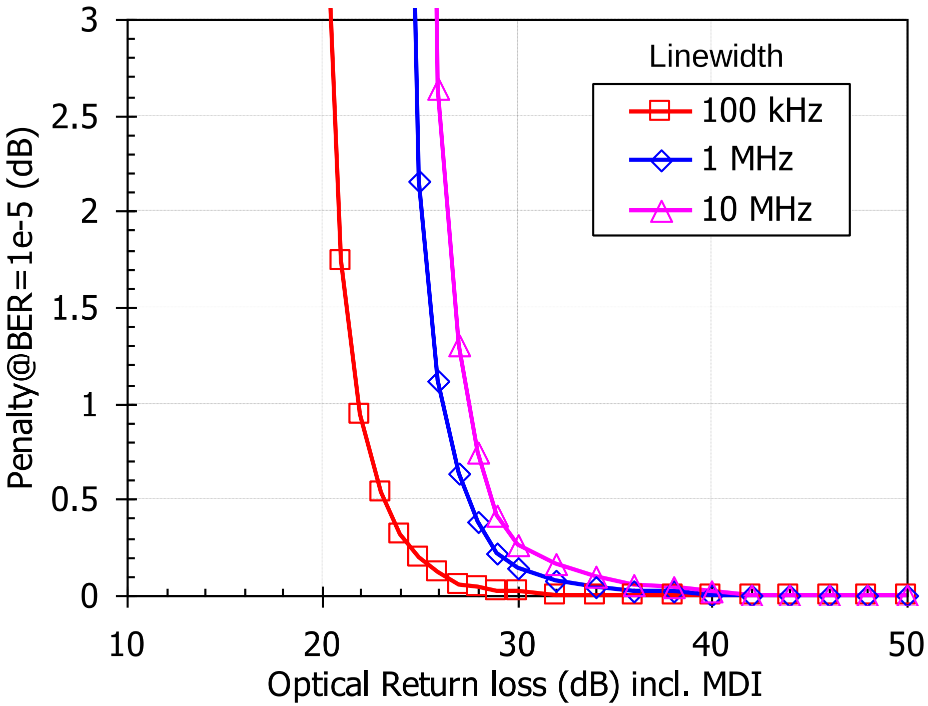
Comparison – Linewidth Dependence

Single trunk model (6 connections including MDI), 500 m link length, all connections have same R.L.

Table. Calculation parameters

Parameters	Value	Units
Modulation Format	PAM-8	-
Wavelength	1310	nm
Spectral width	Parameters	MHz
Extinction ratio	6.0	dB
Source RIN	-149	dB/Hz
Responsivity	0.8	A/W
Receiver bandwidth	32	GHz
Input referred noise	15	pA/sqrt(Hz)
Phase difference from direct path signal	90	deg
Connection points	6	-
Optical return loss	Parameter	dB

Assuming all phases worst (90deg):



Result is slightly pessimistic since all 15 reflected signals are the worst-case phase difference (90 deg) from a direct path signal, which may rarely occur.

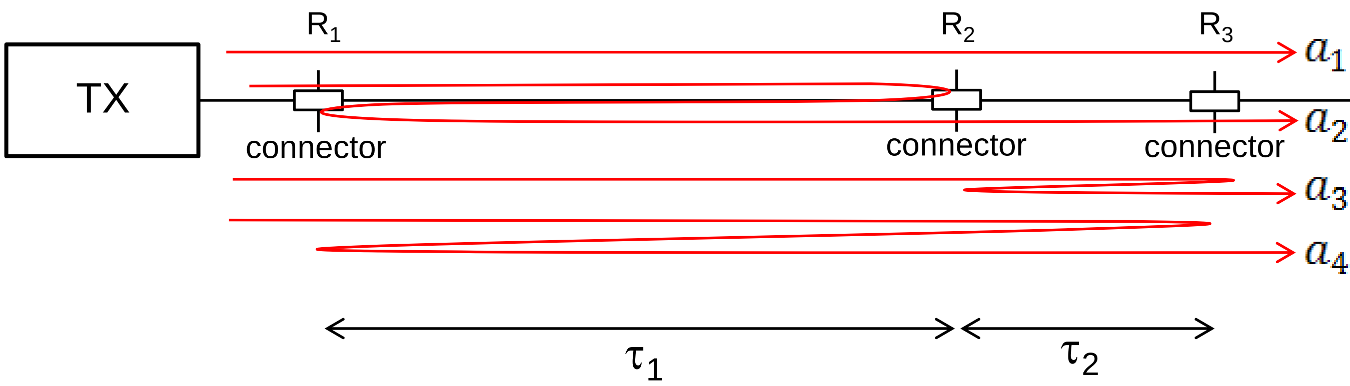
Link RIN approach: Conclusion

- Frequency Domain, Link RIN approach can give us requirement for spectral linewidth of laser source.
- The narrower linewidth laser is, the lower penalty due to less phase-to-intensity noise conversion.

Time Domain Method: Sum of Signals

- Based on explicit sum of amplitudes of all reflections.

  Takes account of fiber loss, number and spacing between connectors, etc.



$$a_1 = s(t-\tau_1-\tau_2)\alpha_1 e^{-j\omega(\tau_1+\tau_2)} e^{-j\varphi(t-\tau_1-\tau_2)}$$

$$a_2 = s(t-3\tau_1-\tau_2)\alpha_2\sqrt{R_1R_2}e^{-j\omega(3\tau_1+\tau_2)} e^{-j\varphi(t-3\tau_1-\tau_2)}$$

$$a_3 = s(t-\tau_1-3\tau_2)\alpha_3\sqrt{R_2R_3}e^{-j\omega(\tau_1+3\tau_2)} e^{-j\varphi(t-\tau_1-3\tau_2)}$$

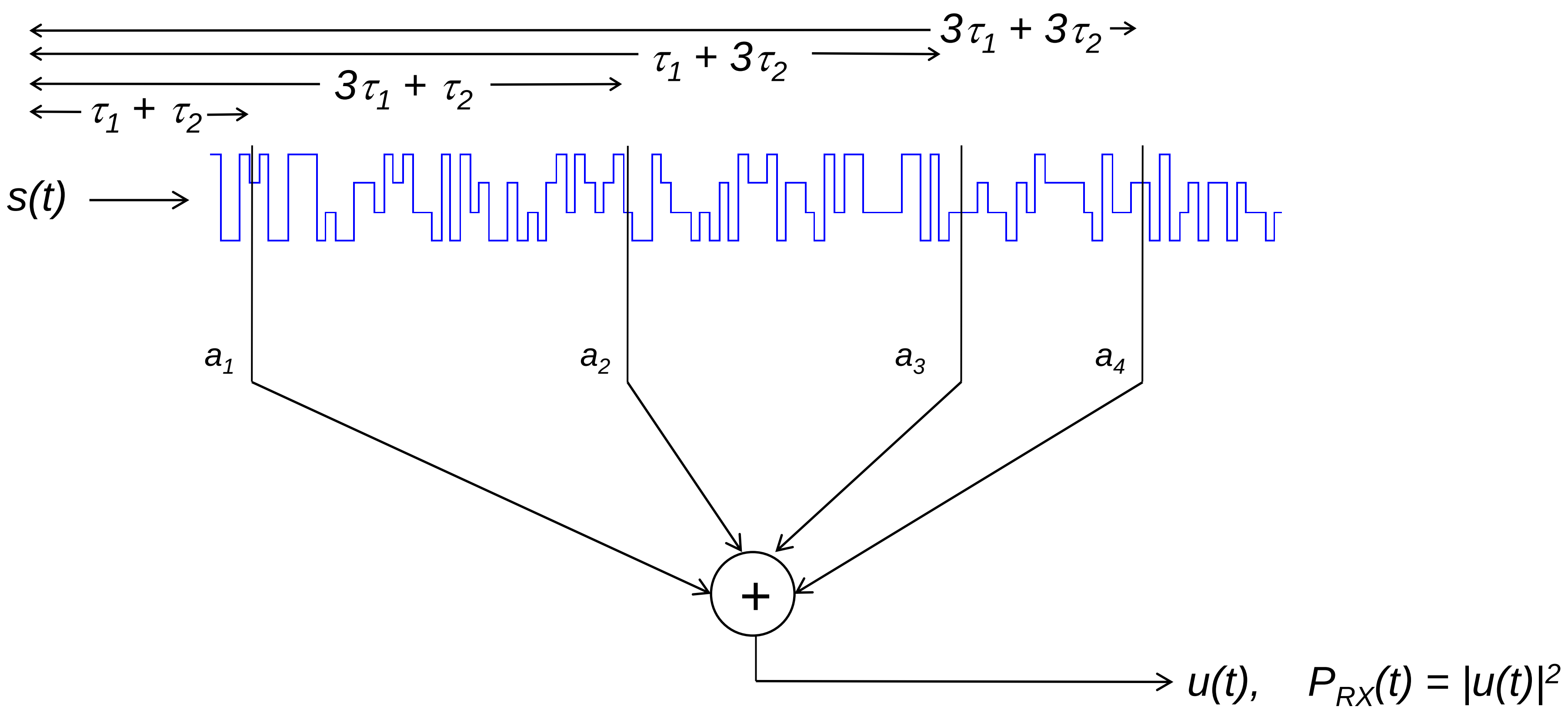
$$a_4 = s(t-3\tau_1-3\tau_2)\alpha_4\sqrt{R_1R_3}e^{-j\omega(3\tau_1+3\tau_2)} e^{-j\varphi(t-3\tau_1-3\tau_2)}$$

s(t) is signal amplitude at time t
φ(t) is the laser phase at time t
$R_{1..3}$ are connector return losses
$A_{1,2}$ account for fiber loss
$\tau_{1,2}$ are path delays

Sum of Signals

- Graphical Representation:

  This is essentially a delayed sample mixing process: a sparse filter.

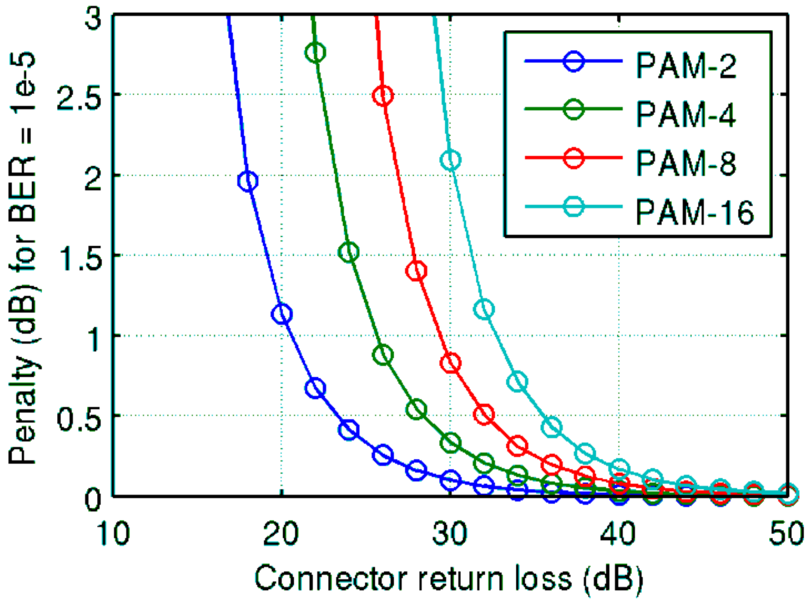


Sum of Signals

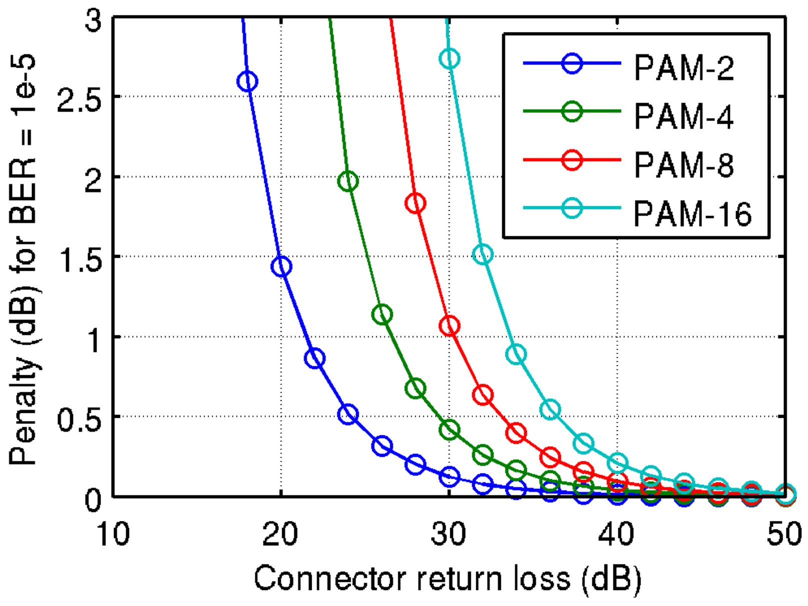
- The phases φ can be taken as i.i.d. random variables on $[0,2\pi)$ as long as $\{2\tau_1;2\tau_2\}$ are greater than the laser coherence time.
  - If they are less than the coherence time, phases are still random, but are not fully independent.
- Monte Carlo approach used to calculate amplitude at RX.
  - Randomize values of s and φ, all of which are uniform random variables.
  - (*s*(t) is a discrete random variable, φ(t) is continuous)
- A histogram can then be calculated which described the power levels seen by the RX for each symbol.
  - By the central limit theorem, the histograms are Guassian, so we can use erfc() to calculate BER and penalty as usual.
- If the path delay differences are less than the laser coherence time, this model will underestimate BER and penalties.
  - This model become more accurate with more connectors and greater link length.

Sum of Signals -- Results

6 reflectance points, 1 km link length, represents 4-connector “Dual Trunk” link



1 dB loss spread over 1 km,
Accounts for attenuation &
connector loss



No connector losses,
No fiber attenuation

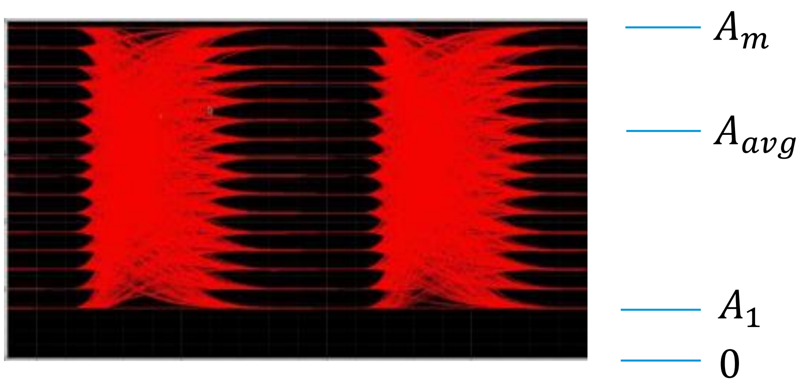
Sum of Signals: Conclusions

- The ‘Sum of Signals’ approach works best for long links or larger number of connectors (>4).
- Can deal with shorter links by creating statistical dependence between phase terms. Results in increased penalty estimates.

Upper-Bound Based Analysis

- Instead of statistical approach, this analysis focuses on upper bound of MPI, for simplicity.
- Starts with the following assumptions:
    - Fiber attenuation and connector losses are zero.
    - All interfering optical signals are perfectly aligned in polarization.

Upper-Bound Analysis: Setup



- For PAM-m, amplitudes $A_i e^{jwt}$, $i = 1\ to\ m,$ are transmitted, each with relative frequency $^1/_m$. At 25G, one symbol time => about 8 mm of fiber.
- Received signal field e(t) = $A_i e^{jwt} + \sum_1^N \sqrt{R^2} A_k e^{j(wt+\hat{\theta})}$ where k is the interfering amplitude number 1..m. $\hat{\theta}$ is a random variable in $[0, 2\pi)$. It accounts for various path lengths of interference etalons, as well as spectral width / phase noise. For a more granular treatment of $\hat{\theta}$ that separately accounts for phase noise and path length, see reference [1].
- N is the number of interfering terms. N = n(n-1)/2, where n is the number of reflectance points in a link, including PMD reflectance points.
- Over thousands of bits, $A_i .. A_N$ interfere in m^N combinations, each equally likely. Any one combination is unlikely to last more than a few bits.

Noise Intensity Upper Bound

- e(t) = $A_i e^{jwt} + \sum_1^N \sqrt{R^2} A_k e^{j(wt+\hat{\theta})}$
- PMD reflectance assumed equal to connector return loss R.
- Assume the worst combination: $A_i = A_m,\ and\ all\ A_k = A_m$. Signal is at highest PAM amplitude, and all interfering terms are of highest PAM amplitude.
- Such a combination has m^(-cN) probability of occurring for c consecutive symbols. Example: PAM-16, 4 connectors, dual trunk, 3 consecutive bit periods for which all interfering terms are at 16th PAM level – probability is 16^(-3*15). (Future work: Use a more realistic assumption.)
- e(t) = $A_m e^{jwt}$ (1 + NR$e^{j\hat{\theta}}$) where NR$e^{j\hat{\theta}}$ is the interference term.
- I(t) = $|e(t)|^2 \cong {A_m}^2$(1 + 2NR$cos\hat{\theta}$), where $2NRcos\hat{\theta}$ is the noise intensity term.
- Since $cos\hat{\theta}$ is bounded within interval [-1, 1],
- Noise Intensity, peak to peak $\leq 4NR{A_m}^2$

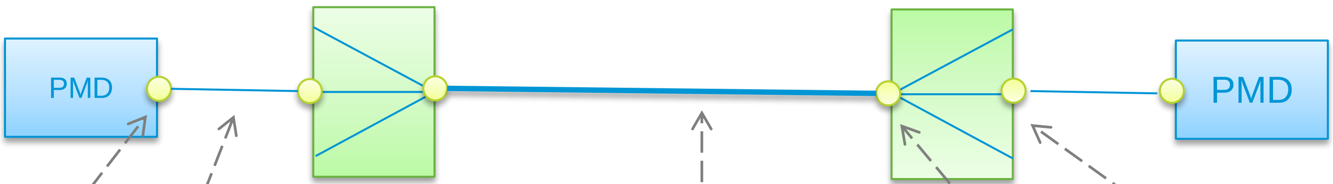
MPI Penalty Upper-Bounds

- MPI Penalty (dB) = 10 Log10 ($\frac{Signal\ Eye\ Height\ without\ MPI}{Reduced\ Signal\ Eye\ Height\ due\ to\ MPI}$)
- MPI Penalty (dB) = 10 Log10 $\left(\frac{OMA}{OMA - 4NRA_m{}^2}\right)$, where OMA refers to eye opening for each of m PAM levels.
- This ensures that there will be NO errors from MPI (zero error rate).
- Substitute OMA = $\frac{A_m{}^2 - A_1{}^2}{(m-1)}$, and note that Extinction Ratio E = $\frac{A_m{}^2}{A_1{}^2}$
- We get MPI Penalty (dB) = 10 Log10 ($\frac{1}{1-x}$), where $x = (m-1)4NR(\frac{E}{E-1})$
- For PAM-8 and PAM-16, results suggest use of return loss 35 dB or better.

MPI Penalty upper bound in dB, for the worst case combination of all reflecting terms at the highest PAM amplitude, zero error rate, Extinction Ratio E = 4 (6 dB), dual-trunk cabling, 4 connectors (six reflectance points, N = 15), m = number of PAM amplitude levels. Results do not include the effect of backscatter.

R (dB)	PAM-2	PAM-4	PAM-8	PAM-16
-26	0.97	4.01	--	--
-30	0.36	1.19	3.57	--
-35	0.11	0.34	0.85	2.07
-40	0.03	0.11	0.25	0.56

Link Configuration – Single Trunk



PMD reflectance point

Duplex SMF equipment cord, 2 to 20 meters.

Patch panel. May have an internal fan-out cable, up to 2 feet long, with MPO connector to connect to trunk, and a duplex UPC connection to equipment cord. Longer trunks may not be pre-terminated; may have just one connection here.

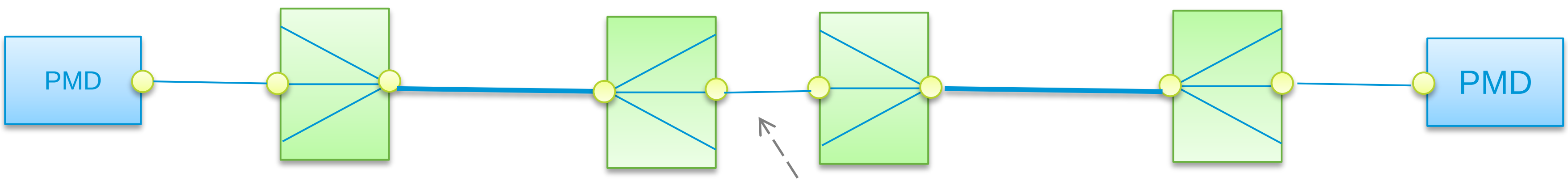
Trunk cable, typically 2x12 fiber. Length 15 to 250 meters (installed base).

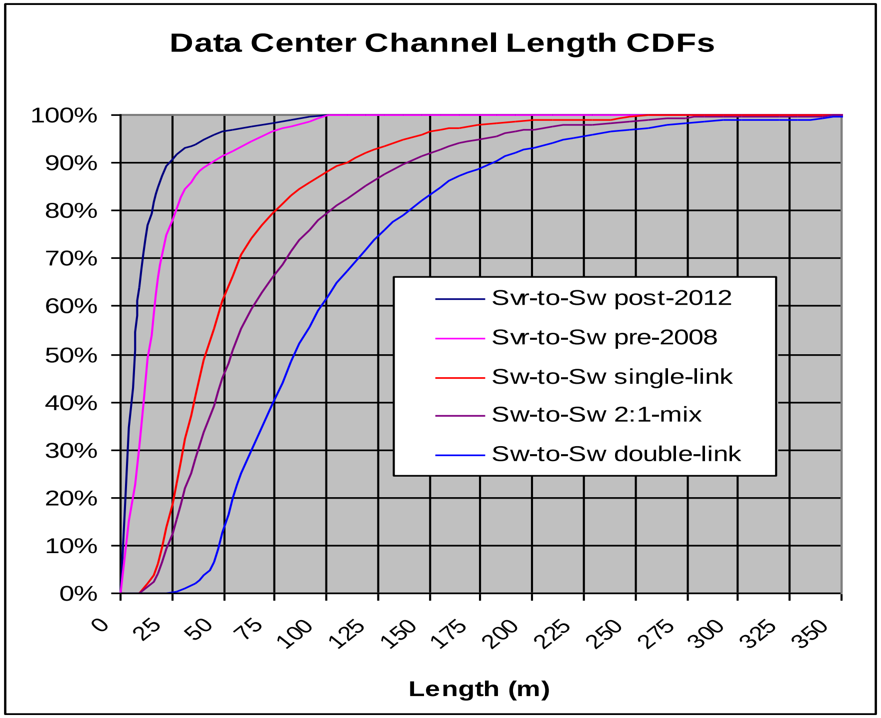
APC connection, multi-fiber MPO connector, negligible (60 dB) return loss.

UPC connection, 40 to 45 dB return loss

This link can be modeled as having total 4 reflectance points -- two UPC connections, plus two PMD interfaces, ignoring the negligible reflectance values of APC connections.

Link Configuration – Dual Trunk





Courtesy: Paul Kolesar, Commscope. [7]

A minority of link cases have dual trunks and two pairs of patch panels. The two patch panels in the middle are connected with short patch-cords. There may be as many as 8 connectors total, although 4 of them would be APC MPO connectors having negligible return loss. The length of the double-link channels runs from about 30 to 400 meters (installed base).

This link can be modeled as having total 6 reflectance points -- four UPC connections, plus two PMD interfaces.

ISO/IEC 11801

- Information Technology – Generic Cabling for Customer Premises

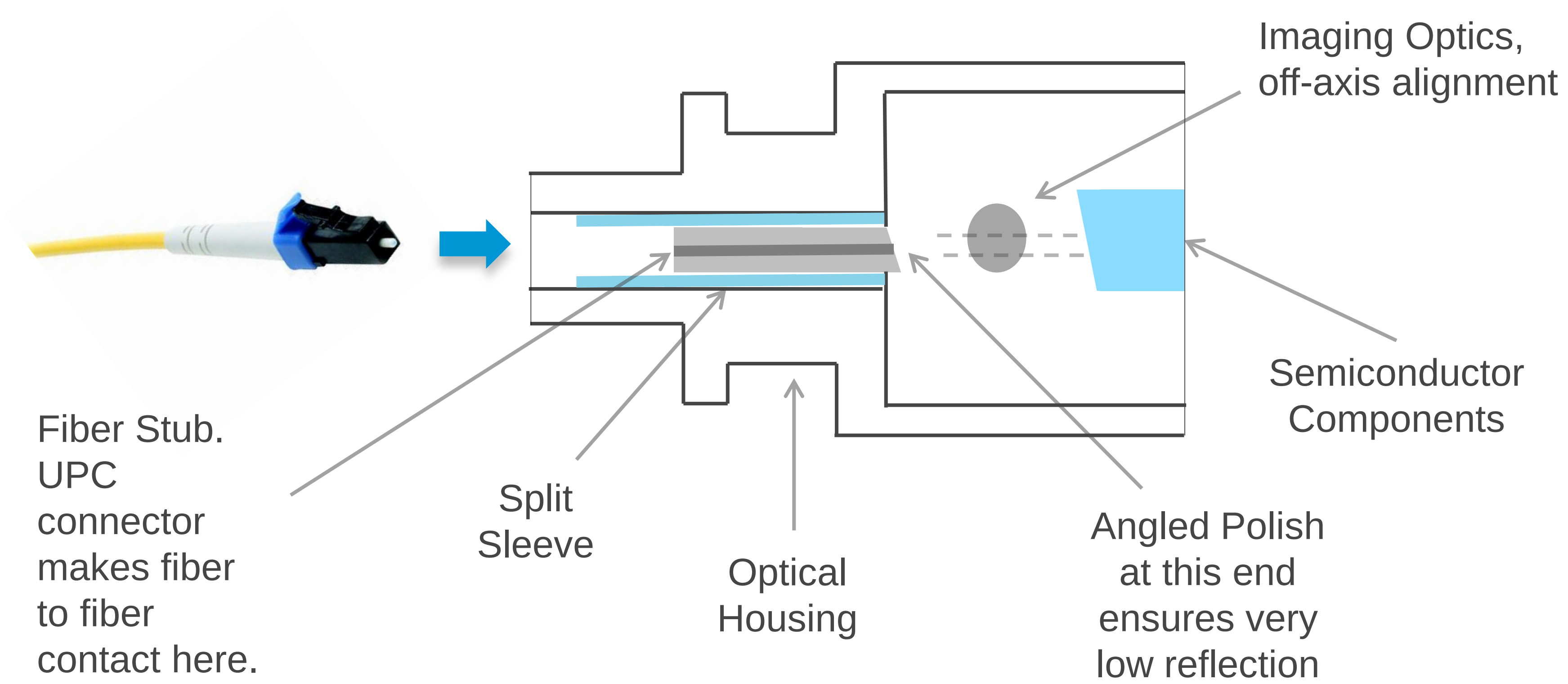
Connector to Connector

ORL	AS/NZS 3080 ISO/IEC 11801	TIA 568.C-3
MMF	-20 dB	-20 dB
SMF	-35 dB	-26 dB
SMF + Video	Not Specified	-55 dB

PMD Reflectance

- PAM-8 and PAM-16 PMD will need a new lower reflectance value, in order to achieve robust performance against MPI.
- We propose a value of 35 dB.
- One option to achieve the same effect is to use APC connector plugs at MDI.
- An option more compatible to installed base is to specify a PMD with low reflectance value. Implementation of this feature is known art. Several feasible and cost-effective implementations exist (stubs, angles, coatings, off-axis optics, etc.)

Low PMD Reflectance: Example



Conclusion

- We have addressed the MPI issue and surveyed three methods – time domain, frequency domain and upper bound. MPI Penalty estimates, in dB:

Frequency Domain Method

R (dB)	PAM-8	PAM-16
-30	< 0.3	
-35	< 0.2	

Matched polarization, all phases at worst case, for 10^-5 error rate.

Time Domain Method

R (dB)	PAM-8	PAM-16
-30	1.0	2.7
-35	0.3	0.7

Matched polarization, random data amplitudes, for 10^-5 error rate.

Upper Bound Method

R (dB)	PAM-8	PAM-16
-30	3.57	High
-35	0.85	2.07
-35	1.10	2.70*

Matched polarization, pathological data pattern of m^(-cN) probability, for zero errors.

* Per Jonathan King. Includes backscatter and APC terms.

- ISO/IEC 11801 Optical Return Loss Specs

Connector to Connector

ORL	AS/NZS 3080 ISO/IEC 11801	TIA 568.C-3
MMF	-20 dB	-20 dB
SMF	-35 dB	-26 dB
SMF + Video	Not Specified	-55 dB

Conclusion, Next Steps

- Per the first two methods presented, the reflectance value should be less than 35 dB for PAM-8 and PAM-16.
- Per the third method, the reflectance value should be less than 35 dB for PAM-8 and probably less than 41 dB for PAM-16.
- The analysis presented here was approximate, and further work should refine it.
- Next steps: Refine the assumptions, improve the analysis.

References

1. "Effects of Phase-to-Intensity Noise Conversion by Multiple Reflections on Gigabit-per-Second DFB Laser Transmission Systems", by Gimlett & Cheung, JOLT Vol. 7, No. 6, June 1989.
2. "Measurements and Simulations of Multipath Interference for 1.7 Gbit/s Lightwave System Utilizing Single and Multi-frequency Lasers", by D. Duff, et al., Proc. OFC, 1989.
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Thank you.