SNR Penalties of SMF PMD Alternatives

400 Gb/s Ethernet Task Force

SMF Ad Hoc Conference Call

5 August 2014

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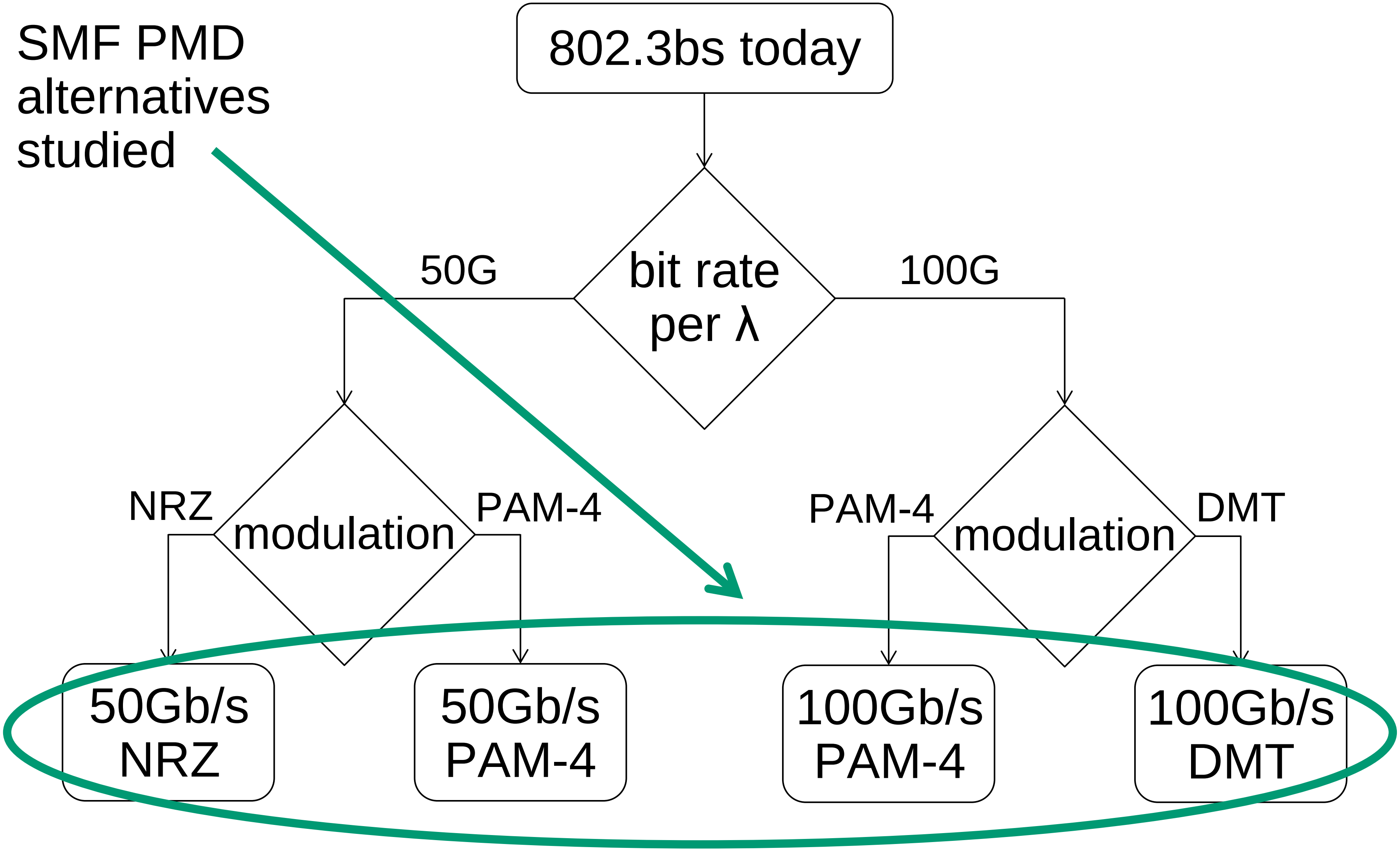
Duplex SMF & PSM4 PMDs Decision Tree

SMF PMD alternatives studied



Introduction

- Bit Rate = Channels * Baud Rate * Bits/Baud
  - Channels = fiber pairs * lambdas * polarizations * I&Qs
  - Baud Rate: proportional to B_{NQ} (Nyquist Bandwidth)
  - Bits/Baud: limited by SNR (Shannon)
- See bliss_3bs_01_0714 for rigorous treatment
- Ex.1: 10GBASE-LR, -SR (1λ)

  10Gb/s = 1 channel * 10GBaud * 1 bit/Baud
- Ex.2: 100GBASE-LR4, -SR4 (4λs or 4 fiber pairs)

  100Gb/s = 4 channels * 25GBaud * 1 bit/Baud
- Ex.3: 100G DP-QPSK Coherent (1λ)

  100Gb/s = 4 channels * 25GBaud * 1 bit/Baud

Bits/Baud Examples

- NRZ: 1 bit/Baud
- PAM-M bits/Baud = log2(M)
  - M=2: 1 bit/Baud
  - M=4: 2 bits/Baud
- QAM-M bits/Baud = log2(√M)) = 0.5*log2(M)
  - M=4: 1 bit/Baud (i.e. $M_I = 2$, $M_Q = 2$)
  - M=16: 2 bits/Baud (i.e. $M_I = 4$, $M_Q = 4$)
- DMT-K QAM-M bits/Baud = log2(√M) = 0.5*log2(M)
  - K is the number of DMT sub-carriers
  - M=4: 1 bit/Baud (i.e. $M_{I\ k=1\rightarrow K} = 2$, $M_{Q\ k=1\rightarrow K} = 2$)
  - M=16: 2 bits/Baud (i.e. $M_{I\ k=1\rightarrow K} = 4$, $M_{Q\ k=1\rightarrow K} = 4$)

Bit Rate Examples

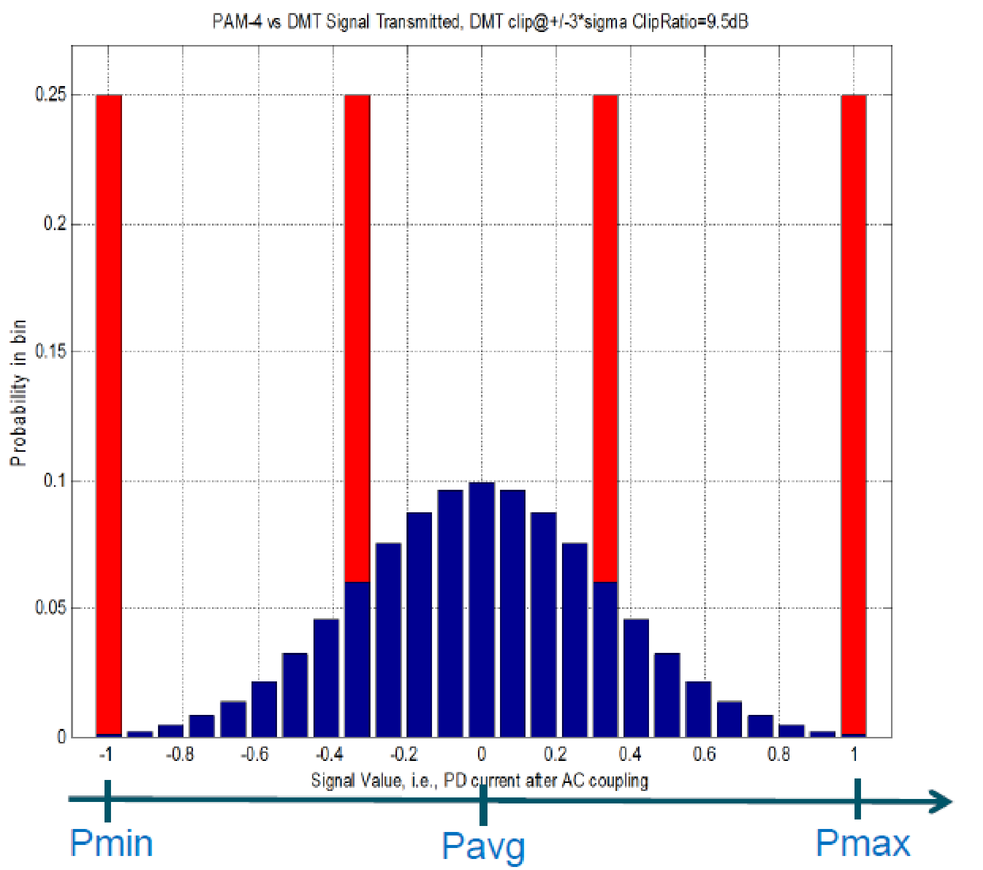
Modulation	Channels	Baud	Bits/Baud	Bit Rate
NRZ	1	2*BW	1	2*BW
PAM-4	1	2*BW	2	4*BW
QAM-16	2	BW	2	4*BW
DMT-K QAM-16	2*K	BW/K	2	4*BW

- $BW = B_{NQ\_PAM-4} = B_{NQ\_QAM-16} = K * B_{NQ\_DMT-K\_QAM16}$
- QAM has 2 channels (I&Q) on one BW/2 sub-carrier
- DMT has K BW/K spaced sub-carriers (1^{st} is BW/(2*K))
- DMT cyclic prefix overhead is ignored in these examples

DMT PAPR Penalty (Electrical) Reference

DMT TX 'SIGNAL VARIANCE' AND CLIPPING

BROADCOM.



- **Red = PAM-4 probability**
- **Blue = DMT example with moderate clipping at +/- 3*sigma**
  - 'Clipping ratio' = 9.5dB
- **Mean time to 'clipping' is about 370 Bauds, so average more than one clip per Block of N=512 Baud samples.**
  - Many blocks will have multiple clippings
- **The 'Signal Variance' (which is communication theory TX power) is 7 dB lower than that of PAM-4**
- **Note that the laser has the same peak-peak power range and equal average power**

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Will Bliss, Advanced Modulation, bliss_3bs_01_0714, p.13

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SNR (Electrical) Examples

Modulation	S	N	SNR
NRZ	P	$2*BW*N_0$	$P/(2*BW*N_0)$
PAM-M	P	$2*BW*N_0$	$P/(2*BW*N_0)$
QAM-M	P/2	$BW*N_0$	$P/(2*BW*N_0)$
DMT-K QAM-M	$\beta_{PAPR}*P/(2*K)$	$(BW/K)*N_0$	$\beta_{PAPR}*P/(2*BW*N_0)$

- S & N are for single channel
- $BW = B_{NQ\_PAM-4} = B_{NQ\_QAM-16} = K * B_{NQ\_DMT-K\_QAM16}$
- N_0 = Noise Power Density (two sided)
- β_{PAPR} = DMT Peak to Average Power Ratio loss coeff.

PAM, QAM SNR Ideal Modulation Penalty (MP)

- All penalties on this and following pages are in dB optical
- PAM-M MP = 10*log10(M-1) dB
  - PAM-2 (NRZ): MP = 0 dB
  - PAM-4: MP = 4.8 dB
  - PAM-16: MP = 11.8 dB
- QAM-M MP = 10*log10(√M -1) dB
  - QAM-4: MP = 0 dB
  - QAM-16: MP = 4.8 dB
  - QAM-256: MP = 11.8 dB
- MP decreases S in SNR therefore:
  - should be shown reducing effective TX power in specs.

DMT SNR Ideal Modulation Penalty (MP)

- DMT-K QAM-M MP = 10*log10(($\sqrt{M}$ -1) / $\sqrt{\beta_{PAPR}}$)
  - β_{PAPR} = DMT PAPR loss coeff.
  - 10*log10(1/$\sqrt{\beta_{PAPR}}$) @ +/- 3σ clipping = 3.5 dB (see p. 6)
  - DMT-K QAM-4: MP = 0 + 3.5 = 3.5 dB
  - DMT-K QAM-16: MP = 4.8 + 3.5 = 8.3 dB
  - DMT-K QAM-256: MP = 11.8 + 3.5 = 14.3 dB
- MP decreases S in SNR therefore:
  - should be shown reducing effective TX power in specs.

SNR Ideal Modulation Bandwidth Penalty (BP)

- BP = 5*log10(B_{SIG}/B_{REF}) dB
  - 25GBaud → 50GBaud: BP = 1.5 dB
  - 25GBaud → 100GBaud: BP = 3.0 dB
- BP increases N in SNR, therefore:
  - decreases RX Sens. in spec. comparisons
- SNR Penalty = SNR MP + SNR BP

SNR Ideal Penalties of 100G PMDs

Modulation	λs	GBaud	BW GHz	Penalty dB
25G NRZ	4	25	12.5	0
50G NRZ	2	50	25	1.5
50G PAM-4	2	25	12.5	4.8
100G PAM-4	1	50	25	6.3
100G PAM-16	1	25	12.5	11.8
100G QAM-16	1	25	25	6.3
DMT-K QAM-16	1	25/K	25	9.8
DMT-K QAM-256	1	12.5/K	12.5	15.3

Ideal KR4, KP4, BCH FEC gains: 2.9, 3.8, 4.3 dB, respectively

SNR Design (Implementation) Penalties

- SNR Design MP (Modulation Penalty)
  - Symbol level accuracy penalty
    - 5% accuracy MP = 0.2 dB
- SNR Design BP (Modulation Bandwidth Penalty)
  - Higher RX device noise penalty
    - 25G → 50G BP = 1.0 dB
  - FEC overhead penalty (PAM & CAP)
    - 3% FEC BP = 0.1 dB
    - 8% FEC BP = 0.2 dB
  - FEC & DMT cyclic prefix penalty (DMT)
    - 12.5% overhead = 0.3 dB

SNR Other Design (Implementation) Penalties

- SNR Other Design Penalties
  - Linear vs. Limiting TIA penalty (AGC noise)
    - penalty = 0.5 dB (was 1.0 dB in cole_3bs_01a_0714)
  - DeMux penalty
    - 2:1 penalty = 1 dB
    - 4:1 penalty = 2 dB
  - Above two penalties affect N in SNR, therefore:
    - affect RX Sens. in spec. comparisons
- More penalties not included in this study:

ER	Mux
CD	EQ Noise Enhancement
Jitter	Quantization
MPI	Crosstalk
Rin	ISI

SNR Ideal + Design Penalties of 100G PMDs

Modulation	λs	GBaud	BW GHz	Penalty dB
25G NRZ	4	25.8	12.9	2
50G NRZ	2	51.6	25.8	3.5
50G PAM-4	2	26.6	13.3	6.5
100G PAM-4	1	55.9	28	8.2
100G PAM-16	1	28	14	12.6
100G QAM-16 DMT K=1, no prefix	1	28	28	8.2
DMT-K QAM-16 K>>1, +/- 3σ clipping	1	29/K	29	11.7
DMT-K QAM-256 K>>1, +/- 3σ clipping	1	14.5/K	14.5	16.4

Effective KR4, KP4, BCH FEC gains: 2.6, 3.2, 3.8 dB, respectively

SNR Penalties of SMF PMD Alternatives

Thank you