Update on Performance Studies of 100 Gigabit Ethernet Enabled by Advanced Modulation Formats

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Outline

- Background
- Simulation Evaluation
  - Penalties due to baseline wander, timing jitter and reflection
  - Link Power Budgets
- Conclusions

Next-Generation Single-Laser 100 Gigabit Ethernet

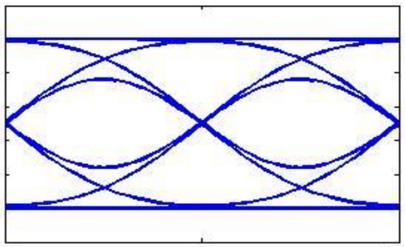
- IEEE 802.3 Next Generation 40 Gb/s and 100 Gb/s Optical Ethernet Study Group proposed PAM
- In addition to PAM, we have proposed 100 Gb/s CAP by using MZMs or directly-modulated lasers (DMLs) together with FEC[1]
- We have also experimentally demonstrated CAP with high power efficiency[1]
- We have also proposed multipulse modulation[2]
- However, the modulation-format-dependent system power penalties due to the following mechanisms were not investigated in our earlier studies[1, 2]
  - Baseline wander
  - Timing jitter
  - Reflection-induced interferometric noise
- In this work, we evaluate the effect of the above mentioned physical mechanisms and provide the corresponding requirements for each modulation format

[1] Jinlong Wei, Jonathan D. Ingham, Richard V. Penty and Ian H. White, "Performance Studies of 100 Gigabit Ethernet Enabled by Advanced Modulation Formats," May 2012, available: http://www.ieee802.org/3/100GNGOPTX/public/may12/ingham_01_0512_optx.pdf
[2] Jonathan D. Ingham, Richard V. Penty, Ian H. White and David G. Cunningham, "Multipulse modulation schemes for 100 Gigabit Ethernet," July 2012, available: http://www.ieee802.org/3/100GNGOPTX/public/jul12/ingham_01a_0712_optx.pdf

Fundamentals of NRZ, PAM and CAP

- **100 Gb/s NRZ**

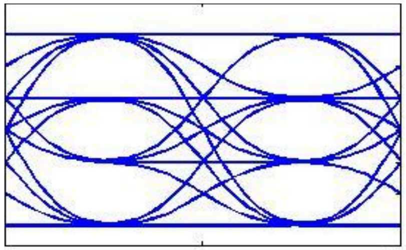
  Symbol rate: 100 Gaud



-T T

- **100 Gb/s PAM-4**

  Symbol rate: 50 Gbaud

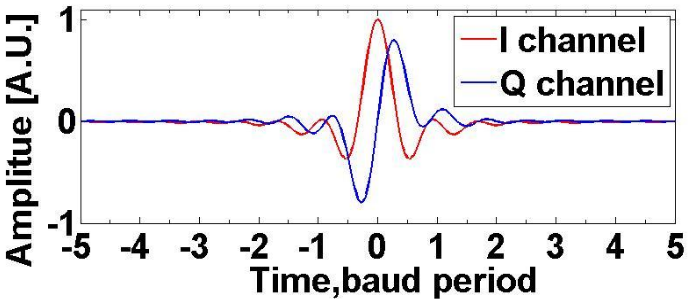


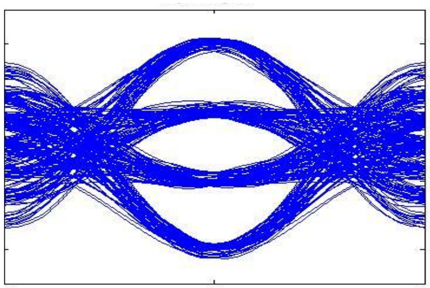
-T T

- **100 Gb/s CAP-16**

  Symbol rate: 25 Gbaud

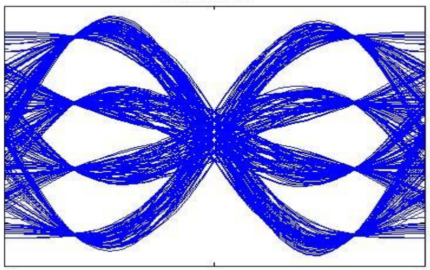
  Roll-off coefficient: 0.25





-T/2 T/2

In-phase



-T/2 T/2

Quadrature

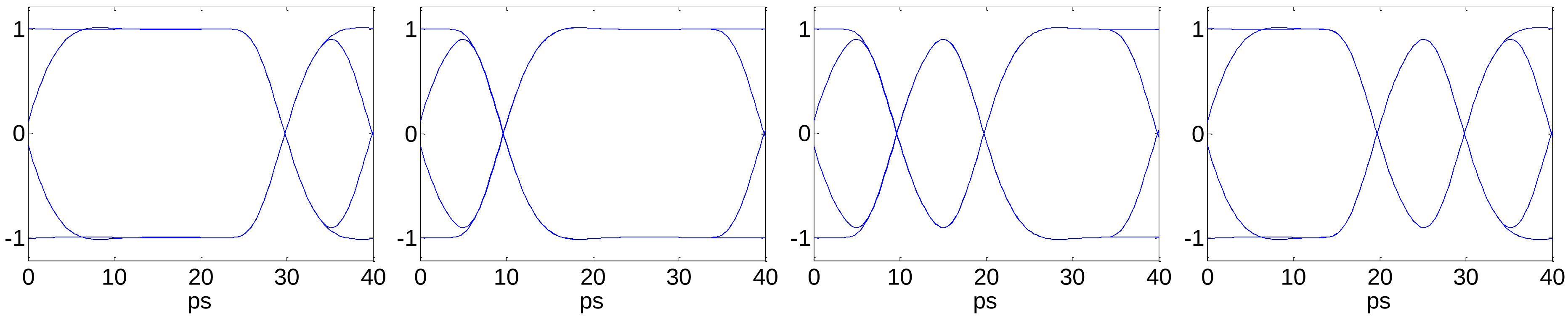
Fundamentals of Multipulse Modulation

- **100 Gb/s multipulse modulation**

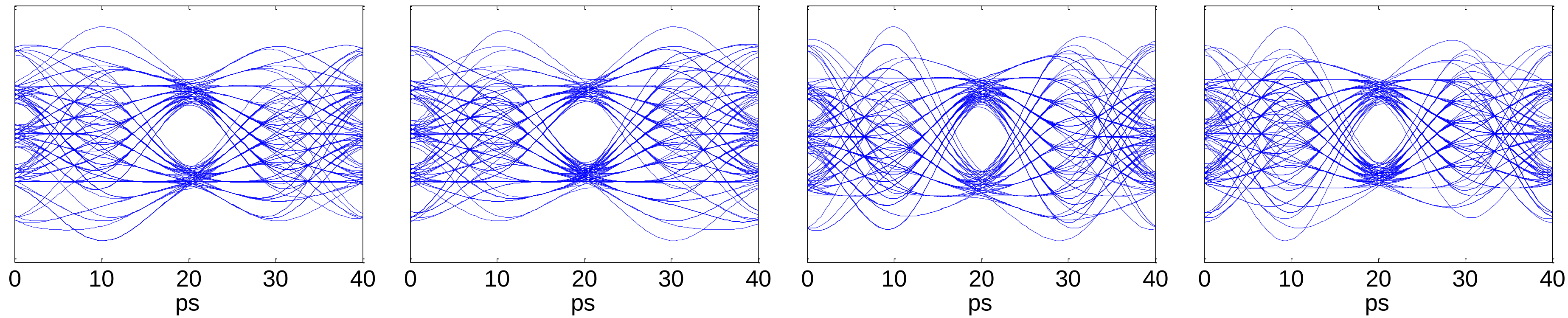
  Symbol rate per pulse: 25 Gbaud

- Modulated “eye” diagrams at output of transmitter

Pulse 1: + + + – Pulse 2: – + + + Pulse 3: + – + + Pulse 4: + + – +



- After matched filter in receiver *with all channels present simultaneously*



Transceiver Component Parameters

component	parameter	value
Laser and modulator	Rise time	10 ps (20% to 80%) with LINEAR response
	RIN	-137.3 dB/Hz
	Wavelength	1300 nm
	MZM frequency response	34 GHz -3 dBe bandwidth 1st order RC response
SMF	Min. dispersion λ	1324 nm
	Laser centre wavelength	1295 nm
	Dispersion slope	0.093 ps/km/nm^2
	Length	500 m to 2 km
Receiver	Filter type	1st order RC response (TIA) [1]
	-3 dBe bandwidth	28 GHz
	Responsivity	0.9 A/W
	Sensitivity	-16.5 dBm @ BER = 10^{-5} for 34.375 Gb/s NRZ system

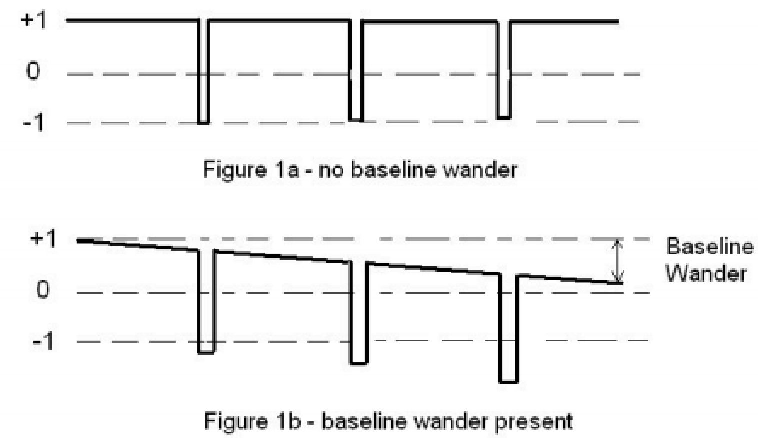
- The parameters are used for all 100 Gb/s systems in this work

- The above reference 34.357 Gb/s NRZ system gives rise to a sensitivity of -18 dBm @ BER = 10^{-3}, indicating total power budget of 18 dB with FEC(10^{-3},10^{-12}) under launch power of 0 dBm

[1] Ali Ghiasi, "PAM-8 Optical Simulations," May 2012, available: http://www.ieee802.org/3/100GNGOPTX/public/may12/ghiasi_01_0512_optx.pdf

Baseline Wander Model for PAM

- The baseline wander induced noise has approximately Gaussian probability distribution[1, 2]
- The variance of the noise is given by[2]



From [2]

$$\sigma^2_{BLwander} = \frac{1}{2}\frac{T}{RC}E\{I_k^2\}$$

T: *PAM symbol period*

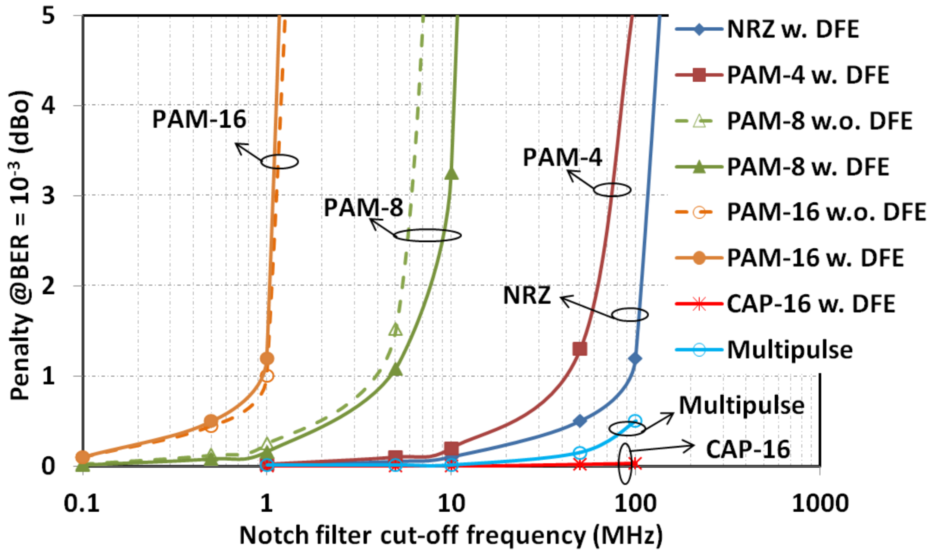
I_k: *Detected symbol levels with k=0, 1, 2,..., M-1 for PAM-M*

RC: $Notch\ \ filter\ \ cut-off\ \ frequency\quad f_c = \frac{1}{2\,\pi\,RC}$

[1] R. Walker, et al., "66b/64b low overhead coding proposal for serial links," Dec. 2000, available: http://www.omnisterra.com/walker/pdfs.talks/dallas.pdf

[2] N. Sommer, et al., "Analysis of the probability distribution of the baseline wander effect for baseband PAM transmission with application to Gigabit Ethernet," 11th IEEE International Conference on Electronics, Circuits and Systems (ICECS), Dec. 2004.

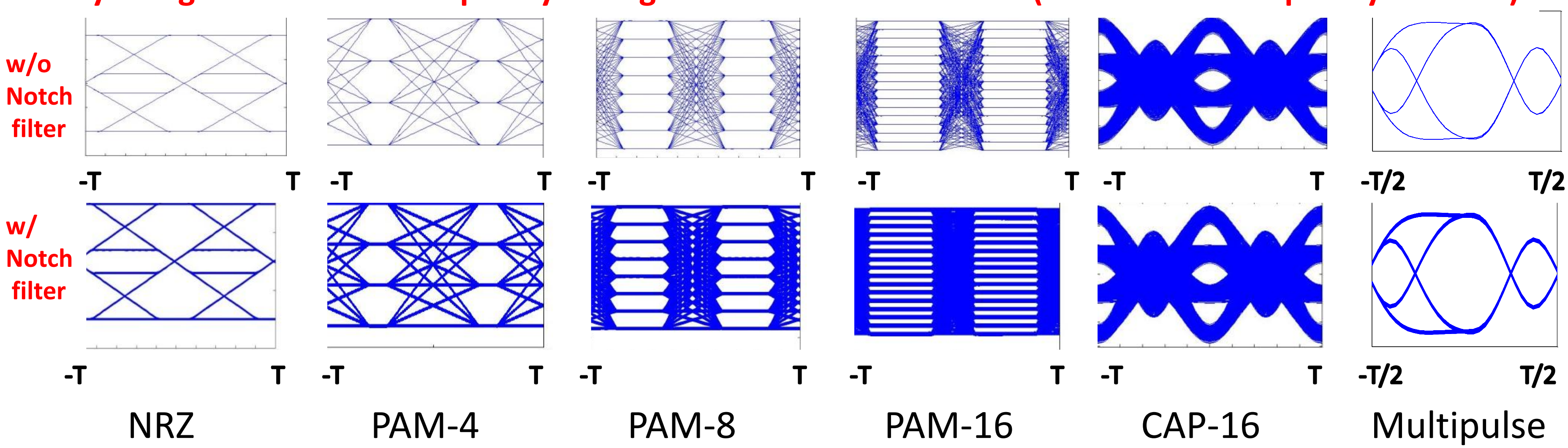
Penalties due to Baseline Wander



DFE: 10 taps T/2 FFE and 3 taps DFE
(except multipulse: interference cancellation applied w/o equalization)

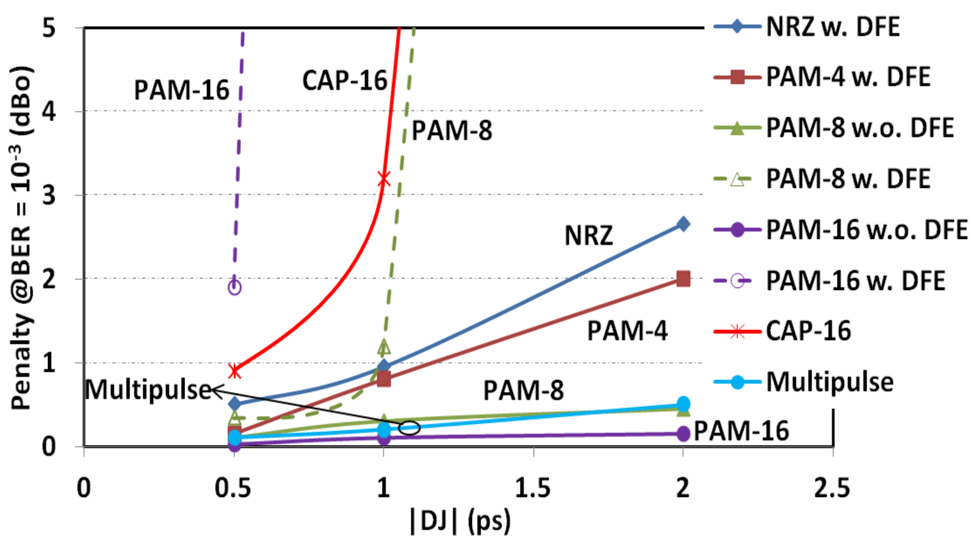
- For PAM schemes, the more levels, the larger the penalty
- The use of DFE for PAM-8 and PAM-16 does not change significantly the penalty
- CAP-16 has the best baseline wander tolerance: approximately zero penalty for notch filter cut-off frequency up to 100 MHz

Eye diagrams for laser output by taking notch filter into account (filter cut-off frequency is 5MHz)

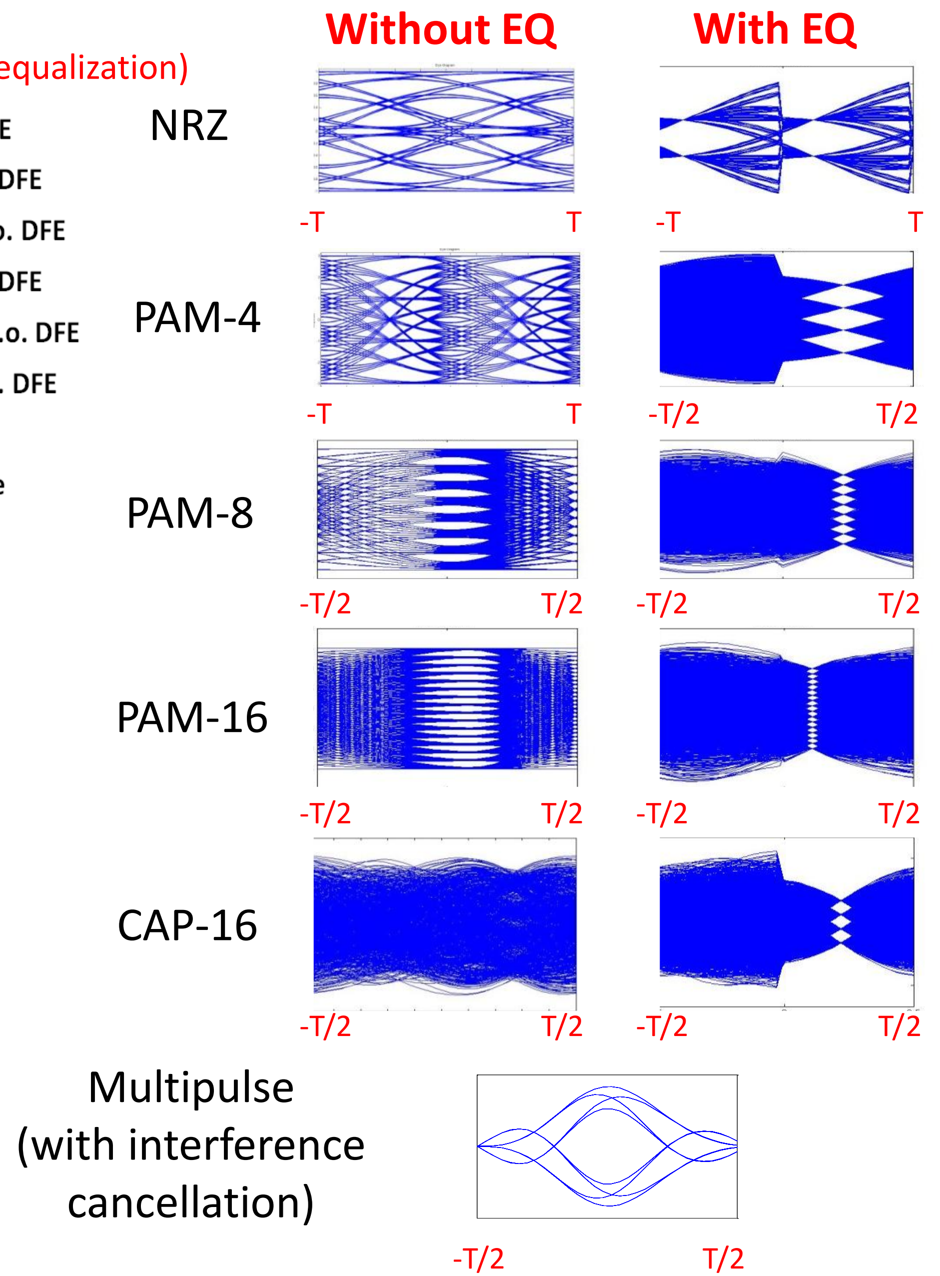


Deterministic Timing Jitter (DJ) Penalty

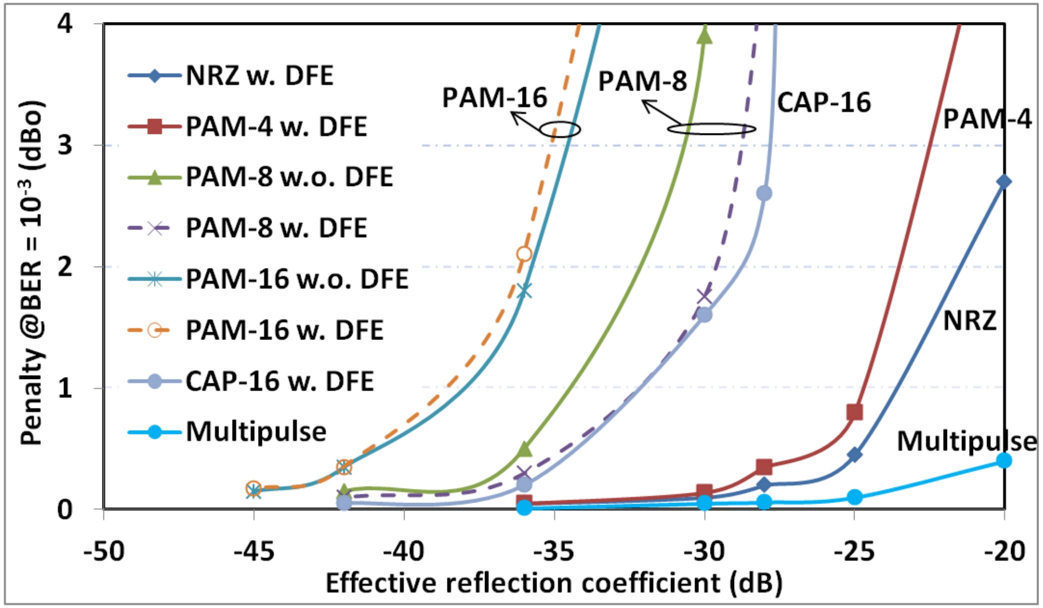
DFE: 10 taps T/2 FFE and 3 taps DFE
(except multipulse: interference cancellation applied w/o equalization)



- Timing jitter calculation is done by offsetting the sampling point in the simulation
- For a target DJ = ±2 ps, PAM-8 with DFE, PAM-16 with DFE and CAP-16 with DFE do not perform well
- PAM-8 without DFE and PAM-16 without DFE have quite low jitter penalty, though are sensitive to baseline wander
- A simple CDR will not work well for PAM-8 with DFE, PAM-16 with DFE and CAP-16 with DFE: a more advanced signal recovery method is required



Reflection-Induced Interferometric Noise Penalty



DFE: 10 taps T/2 FFE and 3 taps DFE
(except multipulse: interference cancellation applied w/o equalization)

- The smaller number of levels PAM has, the smaller the penalty is
- The trend agrees with [1]

No. of intermediate connectors	Effective reflection coefficient (dB)
0	-54
4	-42
10	-36

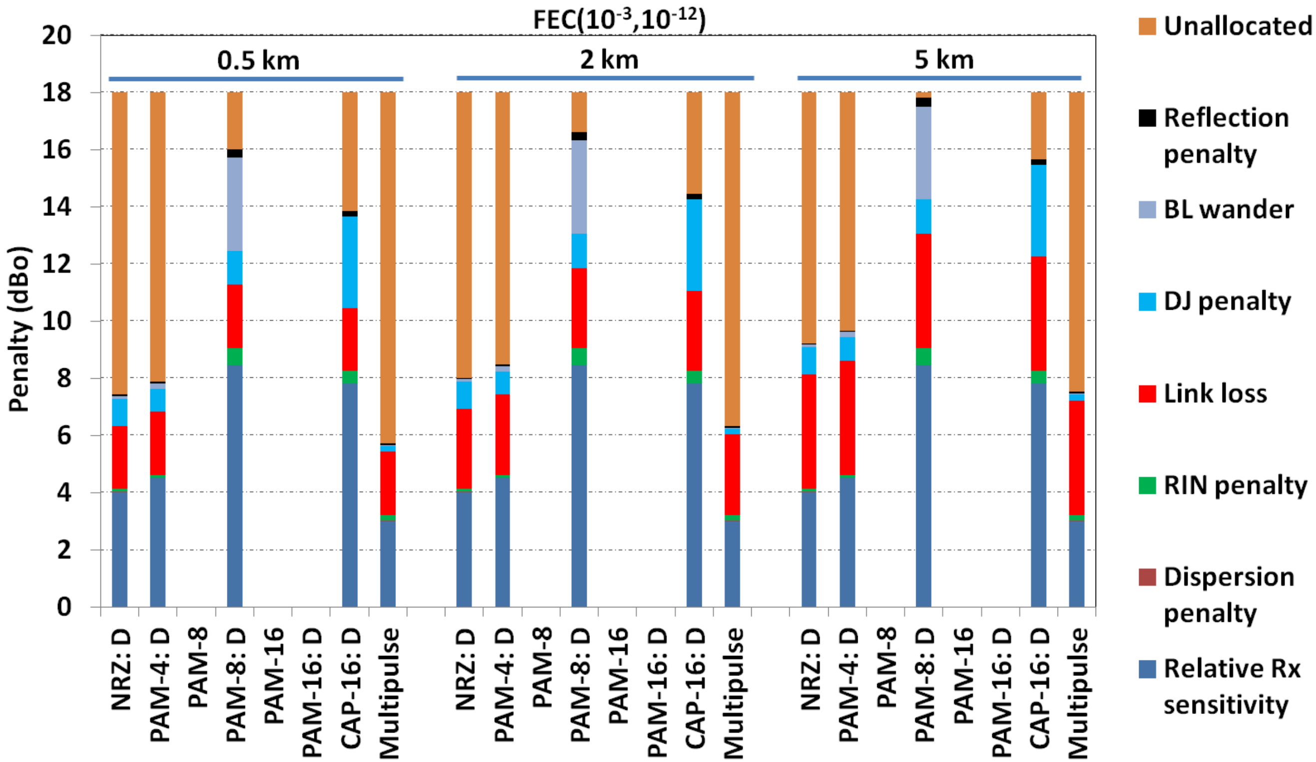
[1] G. Nicholl, et al., “Update on technical feasibility for PAM modulation”, Mar. 2012, available: http://www.ieee802.org/3/100GNGOPTX/public/mar12/plenary/nicholl_01b_0312_NG100GOPTX.pdf

Requirements

	NRZ	PAM-4	PAM-8		PAM-16		CAP-16	Multipulse
EQ	w/ DFE	w/ DFE	w/o DFE	w/ DFE	w/o DFE	w/ DFE	w/ DFE	w/o DFE
BL wander penalty *	high	high	very high	very high	very high	very high	negligible	low
DJ penalty **	high	high	low	high	low	very high	high	low
Reflection penalty***	low	low	medium	medium	high	high	medium	low
Requirements	Notch filter fc < 100 MHz	Notch filter fc < 50 MHz	Notch filter fc < 10 MHz	CDR supports DJ <= 1 ps and fc < 10 MHz	fc < 1 MHz and reflection < -36 dB	CDR supports DJ <= 0.5 ps, fc < 1 MHz, and reflection < -36 dB	CDR supports DJ <=1.0 ps	Interference cancellation scheme in receiver

* Notch filter with cut-off frequency of 10 MHz is considered; ** DJ of ±2 ps is considered;
*** Effective reflection coefficient of -36 dB is considered

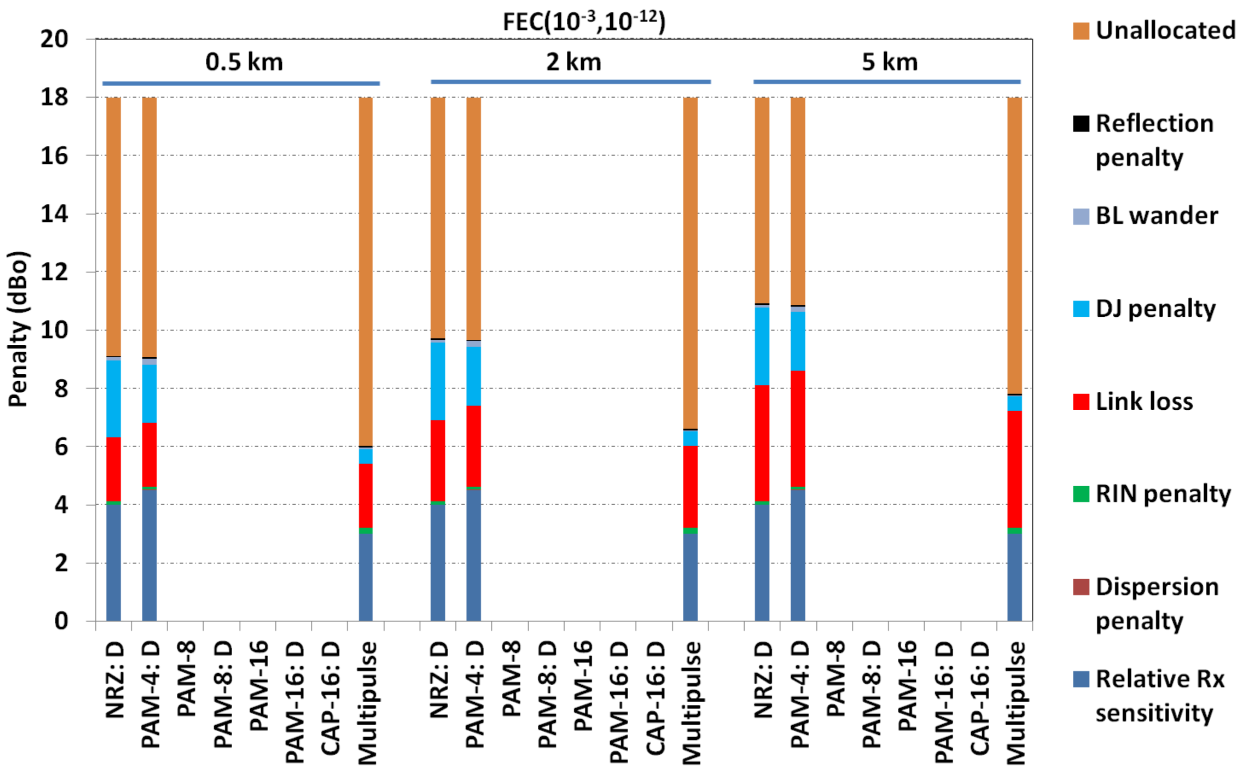
System Power Budgets with DJ of ±1 ps



DFE: 10 taps T/2 FFE and 3 taps DFE
(except multipulse: interference cancellation applied w/o equalization)

- Notch filter cut-off frequency = 10 MHz and reflection coefficient of -36 dB (corresponding to 10 intermediate connectors in the link) are considered
- NRZ with DFE, PAM-4 with DFE, PAM-8 with DFE, CAP-16 with DFE and multipulse support transmission up to 5 km SMF

System Power Budgets with DJ of ±2 ps



DFE: 10 taps T/2 FFE and 3 taps DFE
(except multipulse: interference cancellation applied w/o equalization)

- Notch filter cut-off frequency = 10 MHz and reflection coefficient of -36 dB (corresponding to 10 intermediate connectors in the link) are considered
- Only NRZ with DFE, PAM-4 with DFE and multipulse successfully support transmission up to 5 km SMF

Conclusions

- We have investigated the effect of baseline wander, DJ and reflection-induced interferometric noise on the performance of 100 Gb/s NRZ, PAM-4, PAM-8, PAM-16, CAP-16 and multipulse systems
- Requirements in order to successfully support 100 Gb/s transmission over SMF have been listed for each modulation format
- The link power budgets for various 100 Gb/s systems have been analysed and compared by taking into account baseline wander, DJ and link reflection