Further discussion of DGD penalty and specification for 800G LR4

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IEEE P802.3df 200 Gb/s, 400 Gb/s, 800 Gb/s, and 1.6 Tb/s Ethernet Task Force

Outline

1) Further discussion of G.652.B/D PMD specifications
   - Extended fiber manufacturer overview
   - Impact of segmented cables on fiber PMD
2) Follow up on DGD penalty assessment for 200G PAM4
   - DGD penalty verified by measurements
   - Combined penalty of CD+DGD (numerical)

DGD_{max} Evolution in IEEE standards

- The last major change in PMD specifications happened for 100G/lane PAM4 when G.652.A/C fibers were removed from consideration
- anslow_3cu_01_0519 derived a hypothetical worst case distribution for a single section cable to match PMD_Q = 0.2ps/√km (link design value for 20 fiber segments)
- The maximum individual fiber PMD coefficient for G.652.B/D was assumed to be 0.43ps/√km

Standard	PMD_Q [ps/√km]	PMD_{max} [ps/√km]	DGD_{max} [ps]	Penalty	Reference
10GBASE-LR	0.5	0.8	10	0.1 dB	*P802.3ae Equalization Ad Hoc*
40GBASE-LR4	0.5	0.8	10		Anslow_04_1108
100GBASE-LR4	0.5	~0.7	10→8	0.4dB →0.2 dB	
50GBASE-LR, 200GBASE-LR4, 400GBASE-LR8	0.5	~0.7	8	/	
100GBASE-LR, 400GBASE-LR4	0.5 0.2	~0.7 0.43	8 →5	0.6 dB →0.25 dB	anslow_3cu_01_0519 ITU-T G.652 (2016) updated fiber types. No G.652.A/C with PMD_Q=0.5
100GBASE-FR 400GBASE-FR4	0.2	0.43	2.3	~0dB	Lewis_3cu_02_0719
4×200G FR4	**0.2**	**0.43**	**2.28**	**<0.2dB**	kuschnerov_3df_01b_221012
4×200G LR4	**0.2**	**0.43**	**5**	**<0.7dB**	kuschnerov_3df_01b_221012

$$DGD\_max = PMD\_max * \sqrt{(Lkm)} * 3.75$$

G.652.B/D fiber PMD overview*

Based on publicly available information

Supplier	Country	Fiber type	PMD_Q [ps/√km]	Max PMD individual fiber [ps/√km]
Corning	US	SMF-28 ULL	≤ 0.04	≤ 0.1
Corning	US	SMF-28e+	≤ 0.06	≤ 0.1
YOFC	China	FullBand Ultra LL	≤ 0.06	≤ 0.1
OFS	Japan	AllWave Low Loss	≤ 0.04	≤ 0.1
OFS	Japan	AllWave	≤ 0.06	≤ 0.1
Hengtong	China	BoneCom LL G.652.D	≤ 0.06	≤ 0.1
Hengtong	China	BoneCom mini-G.652.D	**≤ 0.1**	**≤ 0.2**
Fiber Home	China	FiberHome ULL	≤ 0.04	≤ 0.1
Prysmian	Italy	BendBright-XS	≤ 0.06	≤ 0.1
Prysmian	Italy	G.652.D	≤ 0.08	≤ 0.15
Fujikura	Japan	FutureGuide	≤ 0.04	≤ 0.1
HFCL	Pakistan	Flexi ZWP	≤ 0.06	**≤ 0.2**
Draka (legacy)	US	SMF G652.B	≤ 0.08	**≤ 0.2**

*Extended from kuschnerov_3df_01b_221012

G.652.B/D PMD fiber specifications

- The overview of PMD specifications for G.652.B/D fibers shows that the link design value PMD_Q complies with **≤0.1ps/√km (**vs. **0.2ps/√km** specified now)
- Regarding the maximum individual fiber PMD, all G.652.B/D specifications available to the authors for review complied with **≤ 0.2ps/√km (**vs. **0.43ps/√km** assumed now)
- **Note**: Parameters specified by the fiber manufacturers are given for spooled fibers
- It was discussed in kuschnerov_3df_01b_221012 that cabling doesn't necessarily increase the worst case PMD statistics and can actually decrease it

➔ We believe that the PMD coefficient assumption of ≤ 0.2ps/√km for an individual fiber cable serves as good basis for further discussion and a continuing analysis of cabled fiber PMD specifications seems justified

Segmented fiber cable impact on fiber PMD

- So far, short reach Ethernet specifications assumed a single section cable, which is the worst case scenario regarding the maximum DGD statistics
- johnson_3df_optx_01_220414 suggested that ~5km is a typical maximum cable segment length for pulling through underground ducts or aerial installation
- Cabling statistics vary depending on the operator, country regulations, deployment region (access vs. back bone) and brownfield vs. greenfield deployment
- Splicing of several fibers for a longer fiber cable reduces the maximum PMD coefficient in the fibers according to the law of large numbers

Operator fiber deployment statistics

- Initial survey of tier 1 operators indicates following design rules:
  - Operator 1: **≤3km** cable length
  - Operator 2: **≤5km** cable length (see figure)
  - Operator 3:
    - **≤2.4km** cable length in access networks
    - **≤4.8km** cable length in backbone networks
  - Operator 4: **~6km** cable length (Backbone LEAF, deployment in 2000)
  - Operator 5: **≤3km** cable length
  - Operator 6: **≤2km** cable length
  - Operator 7: **≤6km** cable length in metro core (2-3km typ)
- **Assumption**: A 10km single section cable assumption might be an unrealistic scenario for access/LR links

➔ The initial data suggests a further study on access vs. backbone networks and information gathering from more operators

China Telecom backbone network deployment

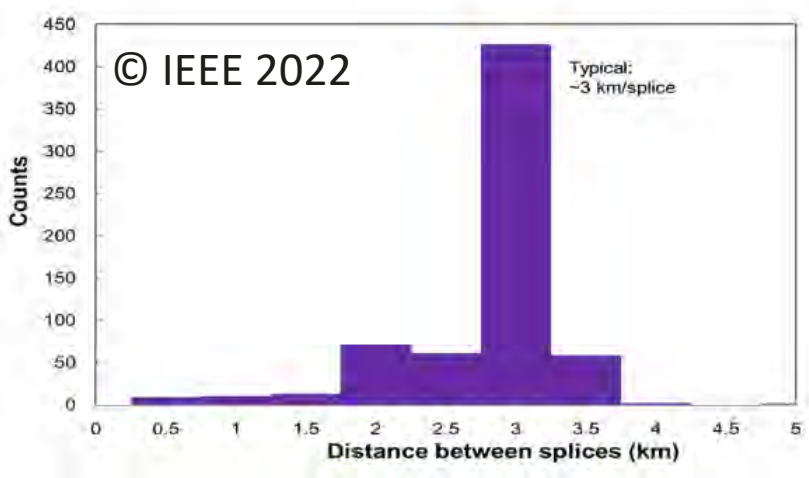
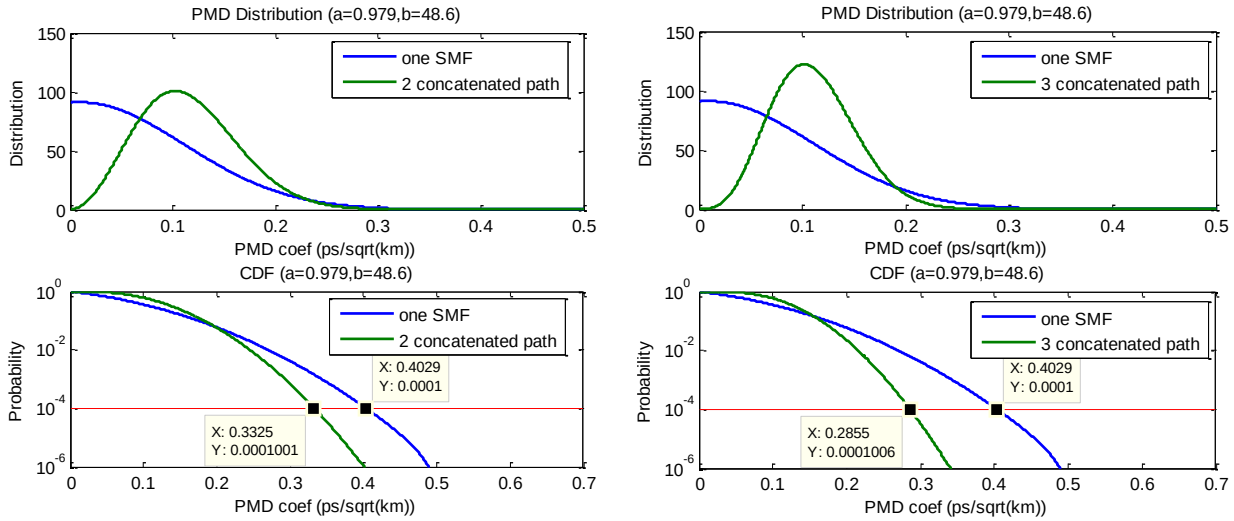


Figure taken from:
Chengliang Zhang et al., "Optical Layer Impairments and Their Mitigation in C+L+S+E+O Multi-Band Optical Networks With G.652 and Loss-Minimized G.654 Fibers", Journal of Lightwave Technology, Vol. 40, No. 11, June 1, 2022, page 3415 ff
https://ieeexplore.ieee.org/document/9756341

Impact of multi-segment links on DGD_{max}

- The concatenation of several fiber cables leads to a reduction of the maximum DGD in the fiber link due to averaging of the PMD coefficient
- Figures on the right show a single cable statistic approximately modelled after anslow_3cu_01_0519
- A concatenation of 2 or 3 cables is able to reduce DGD_{max} accordingly

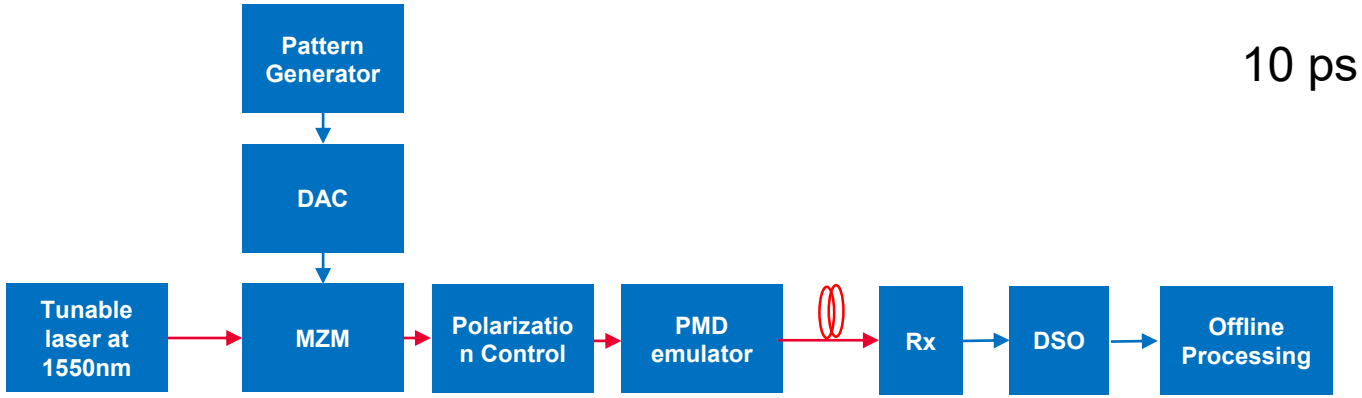
➔ This analysis could be combined with a more realistic maximum individual fiber PMD coefficient



10km	1 section	2 sections	3 sections
PMD_{max}	~0.4 ps/√(km)	0.33 ps/√(km)	0.29 ps/√(km)
DGD_{max}	4.7 ps	3.9 ps	3.4 ps

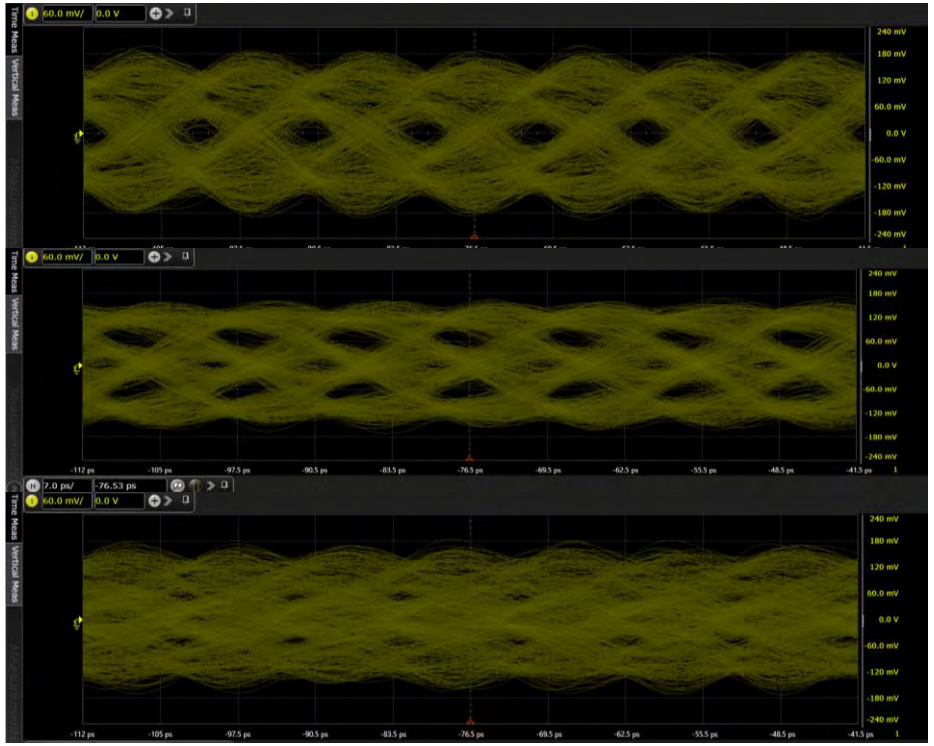
224G PAM4: DGD measurement setup

- To study the measured effect of DGD, the setup below is used
- Since the PMD emulator could only work with C-band optics, a Tx with ECL+MZM in C-band is used
- DGD emulation was characterized using NRZ eye diagrams



DGD measurement setup

100 Gbaud NRZ with DGD

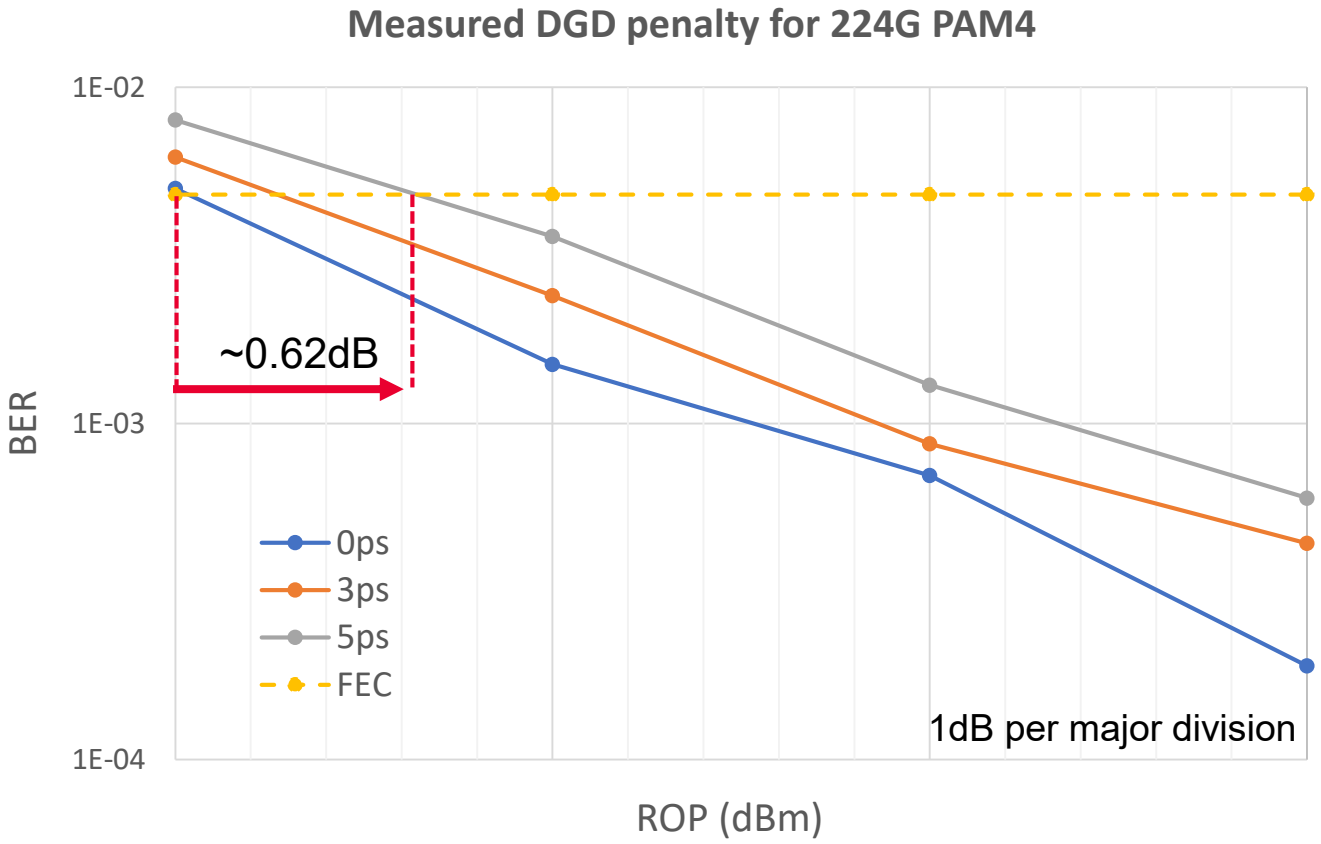


DGD emulator characterization

Measured DGD penalty for 224G PAM4

- At DGD=5ps a penalty of ~0.62dB was measured for the FFE+MLSE receiver
- This corresponds well with the simulations in kuschnerov_3df_01b_221012 where a penalty of <0.7dB was derived for 224Gbit/s PAM4 for several component bandwidth assumptions

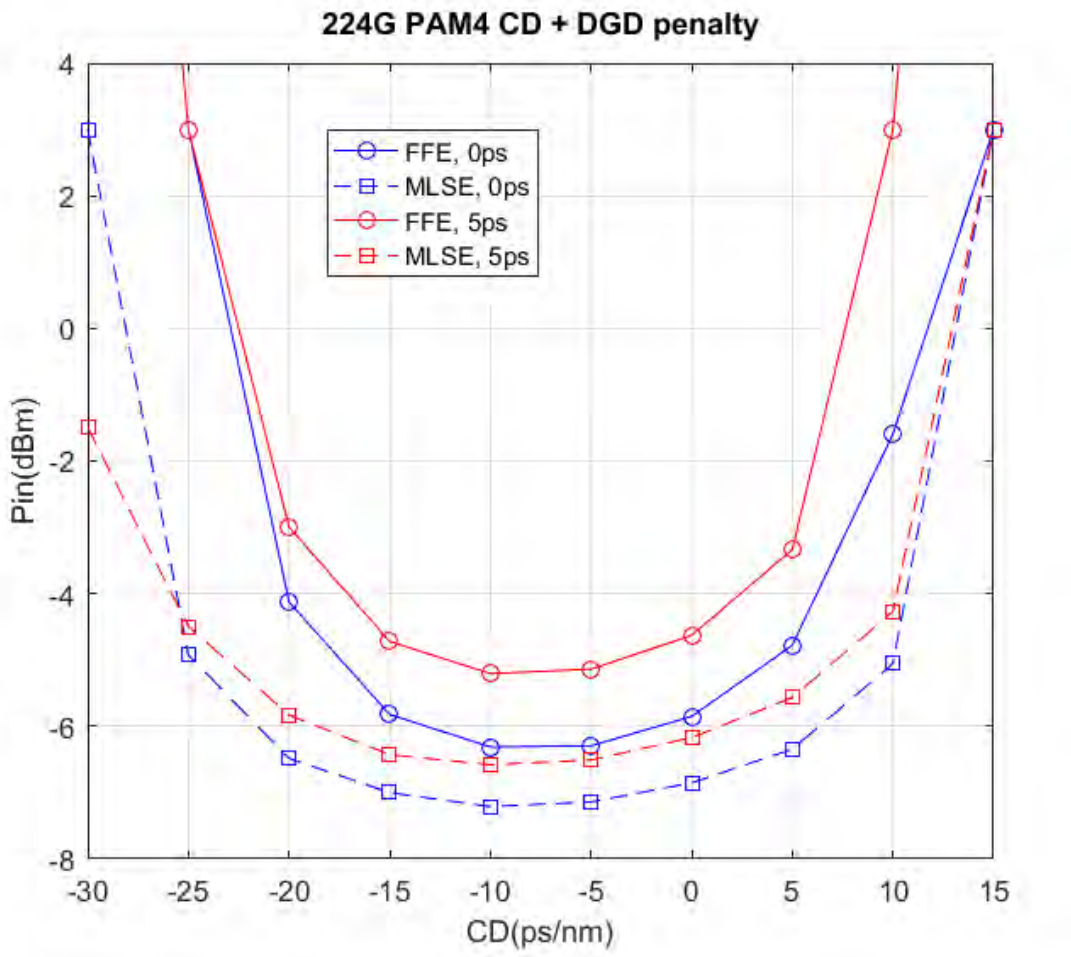
➔ Overall, we believe that this further solidifies the current link budget assumptions for 800G LR4



Combined DGD+CD penalty for 200G PAM4

- During the discussion of kuschnerov_3df_01b_221012 a question was raised whether the penalties of CD and DGD can be added up linearly
- As it is shown on the figure, varying CD doesn't change the baseline DGD penalty
- For very large CD penalty, the CD+DGD penalty becomes less than additive

➔ Adding CD and DGD penalties doesn't underestimate the system impact



Conclusions

- A further analysis of cabled fiber PMD is justified
- More feedback is sought from operators regarding individual cable length statistics before splicing, which could reduce the maximum DGD specification for the 800G LR4 and 1.6T LR8 scenarios
- Numerical verification of DGD penalty for 200G PAM4 was confirmed in measurements
- Adding CD and DGD penalties [dB] doesn’t underestimate the system impact of these two impairments for PAM4 in the CD range of interest

Thank you.