

# An in-depth look at PMD and DGD scenarios for 50 Gbaud, 100 Gbaud and 200 Gbaud IMDD links

Vince Ferretti

Corning

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**CORNING**

# Supporters

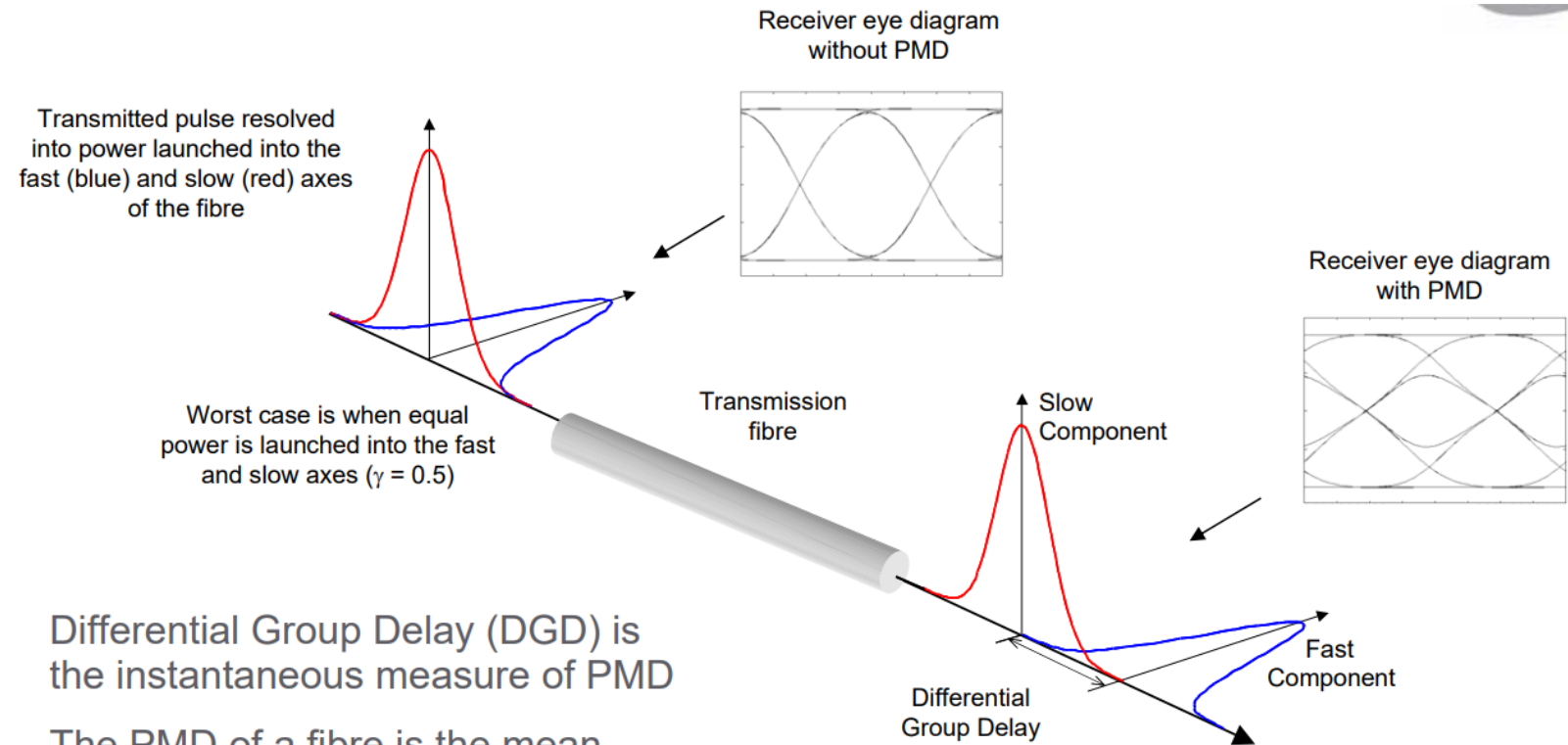
- Frank Effenberger, Futurewei
- John Johnson, Broadcom

# Cable PMD may become a constraint for 100 Gbaud systems and above

- Max allowable Differential Group Delay (DGD) in an IMDD link is dependent on network speed (Gbaud), allowable penalty and probability of failure (time above Max DGD).
- DGD is an instantaneous measure of PMD.
- The PMD of a fiber is the mean value of DGD.
- This presentation will discuss each factor and explore the sensitivity of each.

# Introduction on PMD

[https://www.ieee802.org/3/ba/public/mar08/anslow\\_01\\_0308.pdf](https://www.ieee802.org/3/ba/public/mar08/anslow_01_0308.pdf)



Differential Group Delay (DGD) is the instantaneous measure of PMD

The PMD of a fibre is the mean value of DGD ( $\langle \text{DGD} \rangle$ )

# For IMDD Links less than 10km where $M=1$ , Cable PMD can be derived from anslow\_05\_19

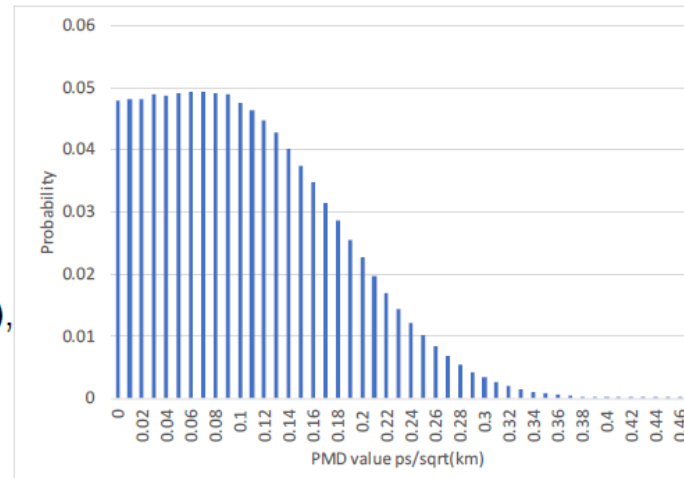
## DGD\_max 2

A more realistic statistical distribution of the cable sections that make up the link would be a mean of  $0.1 \text{ ps}/\sqrt{\text{km}}$  and a standard deviation of  $0.09 \text{ ps}/\sqrt{\text{km}}$  as shown below. This also meets the  $\text{PMD}_Q$  requirement as 20 cable sections taken at random from this distribution have a probability of the combined PMD coefficient exceeding  $0.2 \text{ ps}/\sqrt{\text{km}}$  of 0.009%.

If the 10 km link is only 1 cable section, the probability of the PMD coefficient exceeding  $0.43 \text{ ps}/\sqrt{\text{km}}$  is 0.012%.

$0.43 \text{ ps}/\sqrt{\text{km}}$  for a 10 km link corresponds to a mean DGD of 1.36 ps.

If the ratio of “Max” DGD to mean DGD is set to 3.75 (see page 8 [anslow\\_01\\_0308](#)), this corresponds to a DGD\_max of 5 ps.



$0.43 \text{ ps}/\sqrt{\text{km}}$  would also apply for a 1 or 2 km link where  $M=1$

Note: The ITU-T G.652 specification is  $0.20 \text{ ps}/\sqrt{\text{km}}$ , not  $0.2 \text{ ps}/\sqrt{\text{km}}$  as referenced above

A Mean Normalized  $\text{PMD}_Q$  example has been added to ITU-T G.652 Appendix I to predict  $\text{PMD}_Q$  for  $M$  values  $< 20$  and can be referenced down to  $M=4$

- In Appendix I of the recently consented revision of ITU-T G.652, a mean normalized  $\text{PMD}_Q$  was derived as a function of the number of concatenated cables,  $M$ .
- In this calculation, it was assumed that the population of the concatenated cable's PMD can be described with a Maxwellian distribution.
- The  $\text{PMD}_Q$  value of an arbitrary link was then derived based on the following procedure
  - 1) Define a PMD probability by fixing a coefficient for the Maxwell distribution.
  - 2) Set  $M$  value at 4, 10, 20, or 30.
  - 3) Conduct Monte Carlo simulation to derive 50,000 links with the fixed  $M$ .
  - 4) Derive the  $\text{PMD}_Q$  at  $Q=0.01$ .

Table I.6 Example dependence of mean normalized  $\text{PMD}_Q$  and mean normalized DGD on the number of concatenated cable pieces  $M$ .

Number of concatenated cables $M$	Mean normalized $\text{PMD}_Q$	Mean normalized DGD
4	1.32	0.59
10	1.13	0.80
20	1.00	1.00
30	0.96	1.17

- The following equation was fitted to the results: Mean normalized  $\text{PMD}_Q = 1.646 \times M^{-0.163}$
- This equation can be used to calculate the mean normalized  $\text{PMD}_Q$  at other values of  $M$  and multiplied by 0.20 ps/√km to calculate  $\text{PMD}_Q$  values at the ITU-T G.652 specification level of 0.20 ps/√km .
- For example, for  $M=16$ , Mean normalized  $\text{PMD}_Q = 1.646 \times 16^{-0.163} = 1.05$ ;  $\text{PMD}_Q = 1.05 \times 0.20 \text{ ps}/\sqrt{\text{km}} = 0.21 \text{ ps}/\sqrt{\text{km}}$

# PMD penalty corresponding to Bit Period ( $T_B$ )

*A doubling of Gbaud halves bit period*

- In ITU-T G.691, Figure I.3, the total PMD in a link corresponding to a worst-case path penalty of 1 dB is considered.
- *PMD penalty corresponding to  $T_B$  has improved due to equalization and FEC improvements since G.691 was last updated, but using this figure can help us create a historical starting point for further analysis.*
- *The ITU-T analysis was also done for an NRZ link and today's systems are using PAM 4, which is more limiting.*
- *All these factors need to be considered when analyzing current technologies.*
- In the figure, the worst-case penalty (1 dB) is based on a DGD of 30% (0.3) of bit period ( $T_B$ ) in conjunction with the assumption that both principal states of polarization (PSP) carry the same optical power.
- A worst case 0.7dB penalty can also be estimated for the same link. In this case the worst case corresponds to a DGD of  $\sim 26\%$  of  $T_B$ .

Baud rate expressed as  $T_B$

Gbaud	$T_B$ (psec)
50	20
100	10
200	5

# Relationship between Max DGD and mean DGD

## *IEEE 802.3 has been more conservative than ITU-T*

- Due to the statistical nature of PMD, the relationship between maximum DGD and mean DGD can only be defined probabilistically. The probability of the instantaneous DGD exceeding any given value can be inferred from its Maxwellian statistics.
- Therefore, if we know the maximum DGD that the system can tolerate, we can derive the equivalent mean DGD by dividing by the ratio of maximum to mean that corresponds to an acceptable probability.
- While in ITU-T G.691, a ratio of 3 was chosen, in *anslow\_01\_0308*, a ratio of 3.75 was chosen for IEEE 802.3 links.
- The time scale of excursions above the Max limit is on the order of the characteristic time of DGD evolution in the cable, which depends strongly on the cable environment. E.g., if the characteristic time is 1 minute, then for  $S=3.75$ , the duration of each excursion is  $\sim 1$  minute, and the mean time between excursions is  $\sim 23$  years.
- Cables in a controlled indoor datacenter environment (DRn, FR4 links) are likely on the longer end of this timescale, while cables between datacenters in less controlled outdoor environments (LR4 links) will have shorter characteristic PMD times.

### Maxwell distribution "Max" to mean

S Ratio of "Max" to mean	Probability	Time above "Max" limit per year
3	4.2E-05	22 minutes
3.25	6.19E-06	3 minutes
3.5	7.74E-07	24 seconds
3.75	8.21E-08	2.6 seconds
4	7.41E-09	0.2 seconds

The above table needs to be corrected to take account of two factors:

- When the DGD is above the "Max" value, the penalty is only as high as shown on slide 6 when  $\gamma = 0.5$  (equal power in the two axes). For  $S = 3$  (see P802.3ae, Equalization Ad Hoc, [T Hanson](#)) the probability should be multiplied by a factor of 0.25.
- The 100GbE link is made up of 4 lanes so the time above the "Max" limit for the link is  $\sim 4$  x the time above the "Max" limit for each lane.

These effects therefore almost cancel each other out.

*anslow\_01\_0308*



# Max Allowable PMD (ps/T<sub>B</sub>) as a function of Rate, Penalty (dB) and Probability

- If the DGD penalty assumptions on the previous slides are applied, Max PMD allowable in a link = (acceptable percentage of T<sub>B</sub>) \* (1/Ratio of Max to Mean (S)) \* T<sub>B</sub>

Allowable % T <sub>B</sub> (1dB, or 0.7dB penalty)		30%	30%	26%	26%
Ratio of Max to mean (S)		3	3.75	3	3.75
Rate (Gbaud)	Bit period (ps)	Allowable PMD (ps)	Allowable PMD (ps)	Allowable PMD (ps)	Allowable PMD (ps)
50	20	2	1.6	1.7	1.4
100	10	1	0.8	0.9	0.7
200	5	0.5	0.4	0.4	0.3

- Max allowable PMD decreases with higher rate, lower allowable penalty and higher Max to Mean ratio (less time above the Max DGD)

# Max Allowable PMD (ps/ $\sqrt{\text{km}}$ ) for IMDD links from 1 km to 100 km compared to cable PMD<sub>Q</sub>

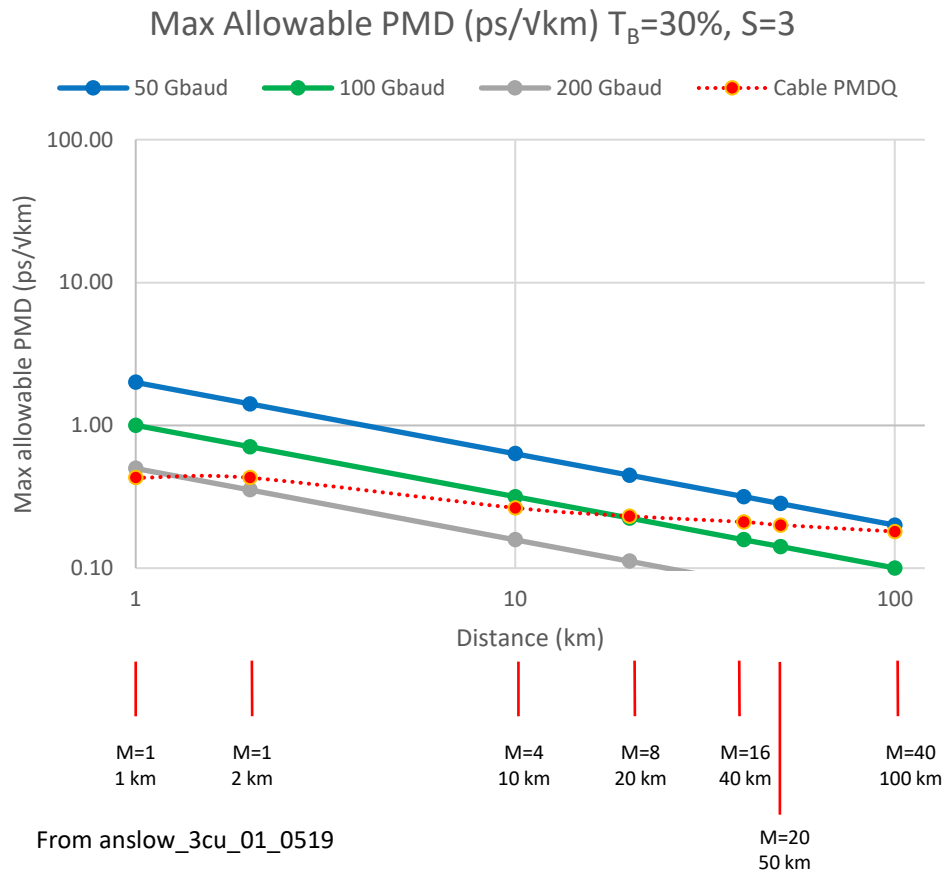
(This table is better described in the graphs on the following slides)

T <sub>B</sub> = 30% S= 3	Distance (km)	1	2	10	20	40	50	100
	50 Gbaud	2.00	1.41	0.63	0.45	0.32	0.28	0.20
	100 Gbaud	1.00	0.71	0.32	0.22	0.16	0.14	0.10
	200 Gbaud	0.50	0.35	0.16	0.11	0.08	0.07	0.05
	Cable PMD <sub>Q</sub>	0.43	0.43	0.26	0.23	0.21	0.20	0.18
T <sub>B</sub> = 30% S= 3.75	Distance (km)	1	2	10	20	40	50	100
	50 Gbaud	1.60	1.13	0.51	0.36	0.25	0.23	0.16
	100 Gbaud	0.80	0.57	0.25	0.18	0.13	0.11	0.08
	200 Gbaud	0.40	0.28	0.13	0.09	0.06	0.06	0.04
	Cable PMD <sub>Q</sub>	0.43	0.43	0.26	0.23	0.21	0.20	0.18
T <sub>B</sub> = 26% S= 3	Distance (km)	1	2	10	20	40	50	100
	50 Gbaud	1.73	1.23	0.55	0.39	0.27	0.25	0.17
	100 Gbaud	0.87	0.61	0.27	0.19	0.14	0.12	0.09
	200 Gbaud	0.43	0.31	0.14	0.10	0.07	0.06	0.04
	Cable PMD <sub>Q</sub>	0.43	0.43	0.26	0.23	0.21	0.20	0.18
T <sub>B</sub> = 26% S= 3.75	Distance (km)	1	2	10	20	40	50	100
	50 Gbaud	1.39	0.98	0.44	0.31	0.22	0.20	0.14
	100 Gbaud	0.69	0.49	0.22	0.16	0.11	0.10	0.07
	200 Gbaud	0.35	0.25	0.11	0.08	0.05	0.05	0.03
	Cable PMD <sub>Q</sub>	0.43	0.43	0.26	0.23	0.21	0.20	0.18

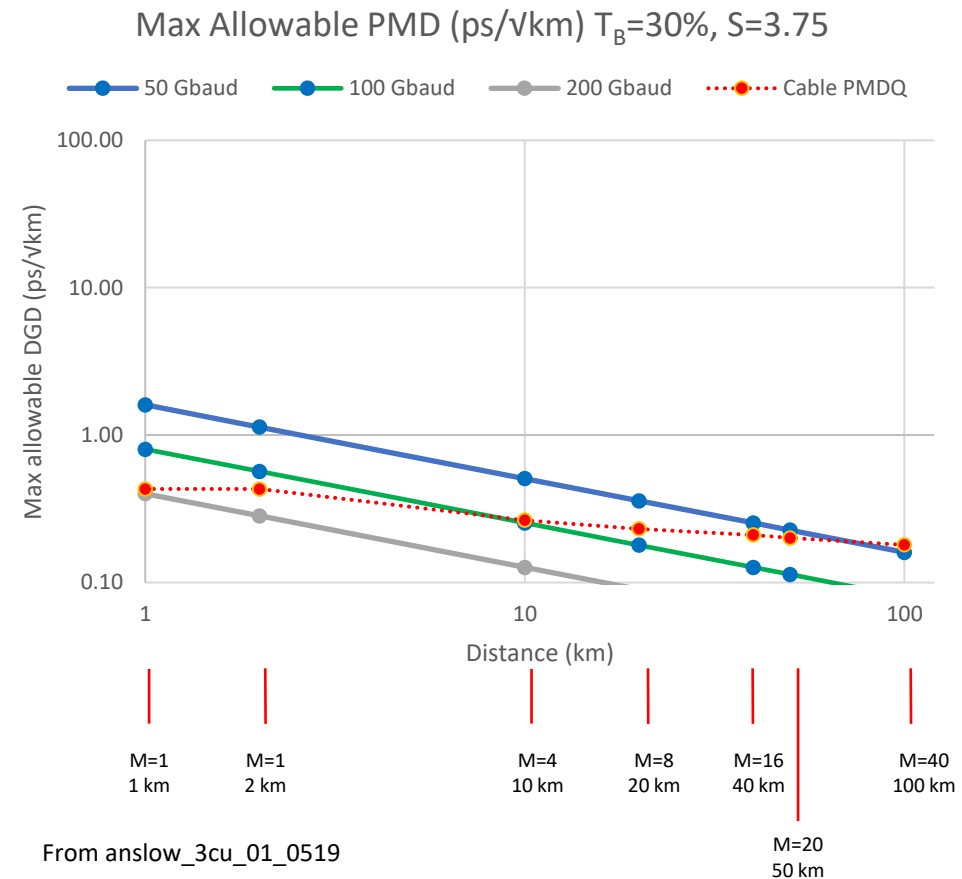
1. Cable PMD<sub>Q</sub> was calculated using the recently added to ITU-T G.652 mean normalized PMD<sub>Q</sub> for lengths 10 km or greater assuming concatenated 2.5km sections.
2. PMD for 1 cable at 1 km and 2 km is derived from anslow\_3cu\_01\_0519 contribution.

# Max Allowable PMD (ps/√km) Scenarios for 1 dB Penalty

*1 dB penalty and S=3 are used in ITU-T G.691 design guide*



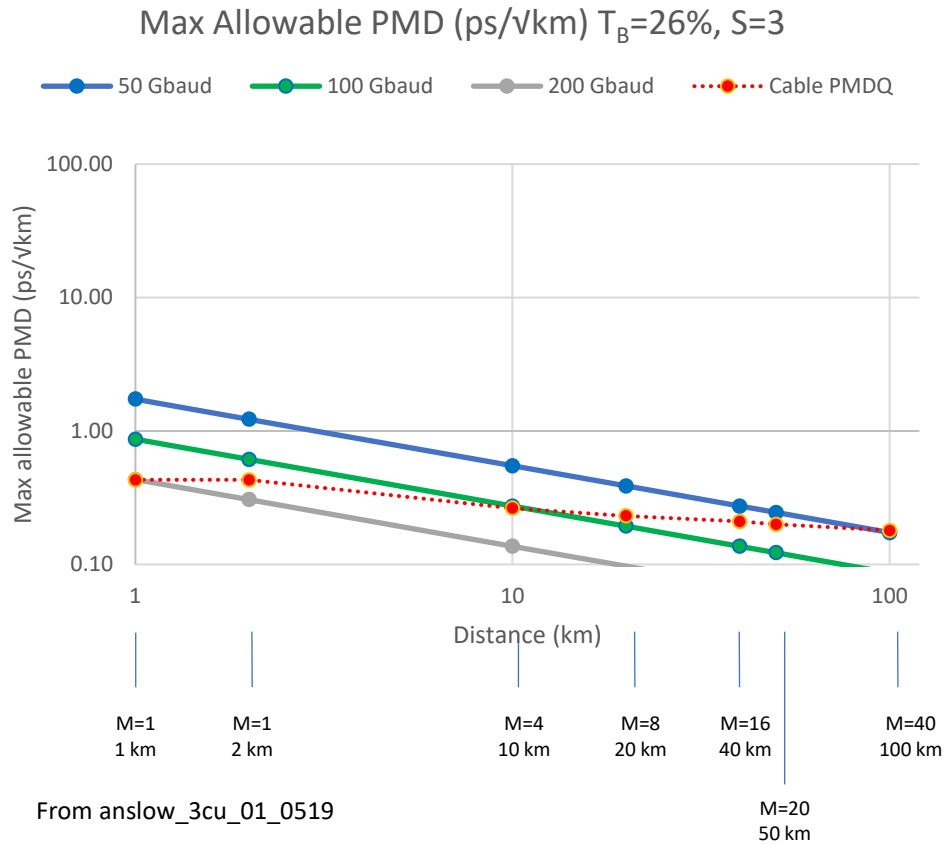
From ITU-T G.652 Appendix I



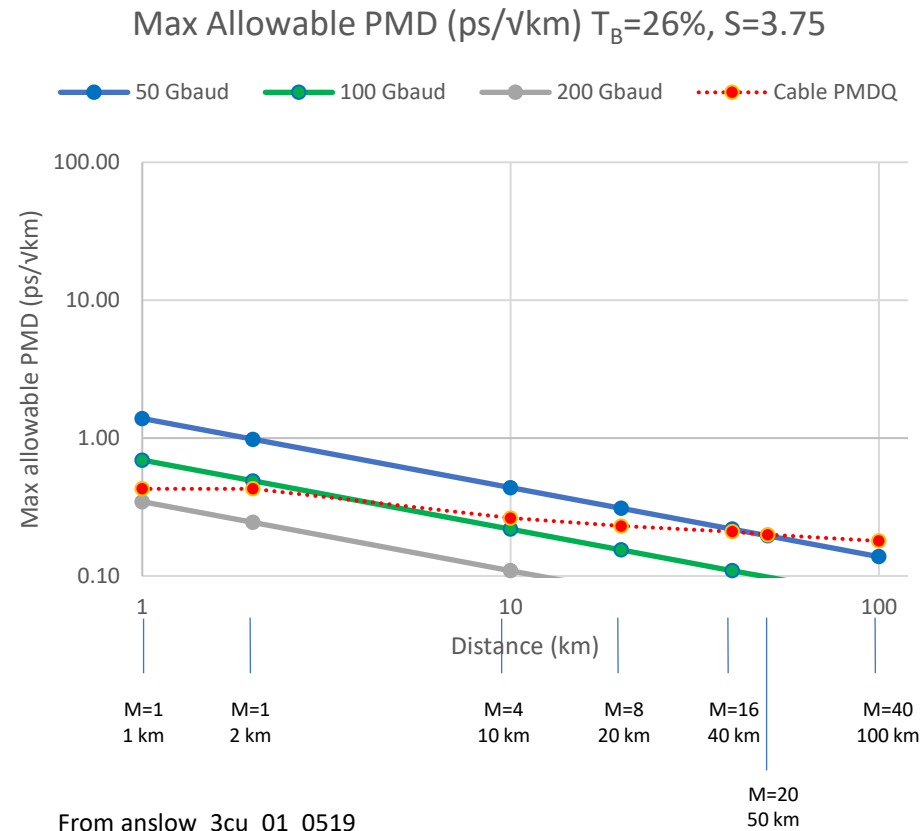
From ITU-T G.652 Appendix I

# Max Allowable PMD (ps/√km ) Scenarios for 0.7 dB Penalty

*IEEE 802.3 has typically used  $S=3.75$  and penalties less than 1 dB*



From ITU-T G.652 Appendix I



From ITU-T G.652 Appendix I

Max DGD using 3.75 ratio can be calculated from  $PMD_Q$

- $\text{Max DGD (ps)} = PMD_Q * \sqrt{\text{km}} * S$

Distance (km)	1	2	10	20	40	50	100
Cable $PMD_Q$ (ps/√km)	0.43	0.43	0.26	0.23	0.21	0.20	0.18
Max DGD (ps) (S= 3.75)	1.61	2.28	3.13	3.87	4.98	5.30	6.75

# Conclusions

- Max allowable PMD in an IMDD link is dependent on network speed (Gbaud), allowable penalty and probability of failure.
- Choosing allowable penalty of 1 dB versus 0.7 dB should be analyzed. PMD penalty corresponding to  $T_B$  may have improved since ITU-T G.691 was last updated.
- Ratio of Max to Mean (S) values of 3 and 3.75 also need to be understood and discussed.
- At 50 Gbaud, a link may work up to ~100km, at 100 Gbaud, ~20km and at 200 Gbaud, ~2 km.
- Cable  $PMD_Q$  can be used to design Max DGD for different link lengths.
- These calculations should be verified through experimentation in the lab and in deployed cables.

THANKS