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

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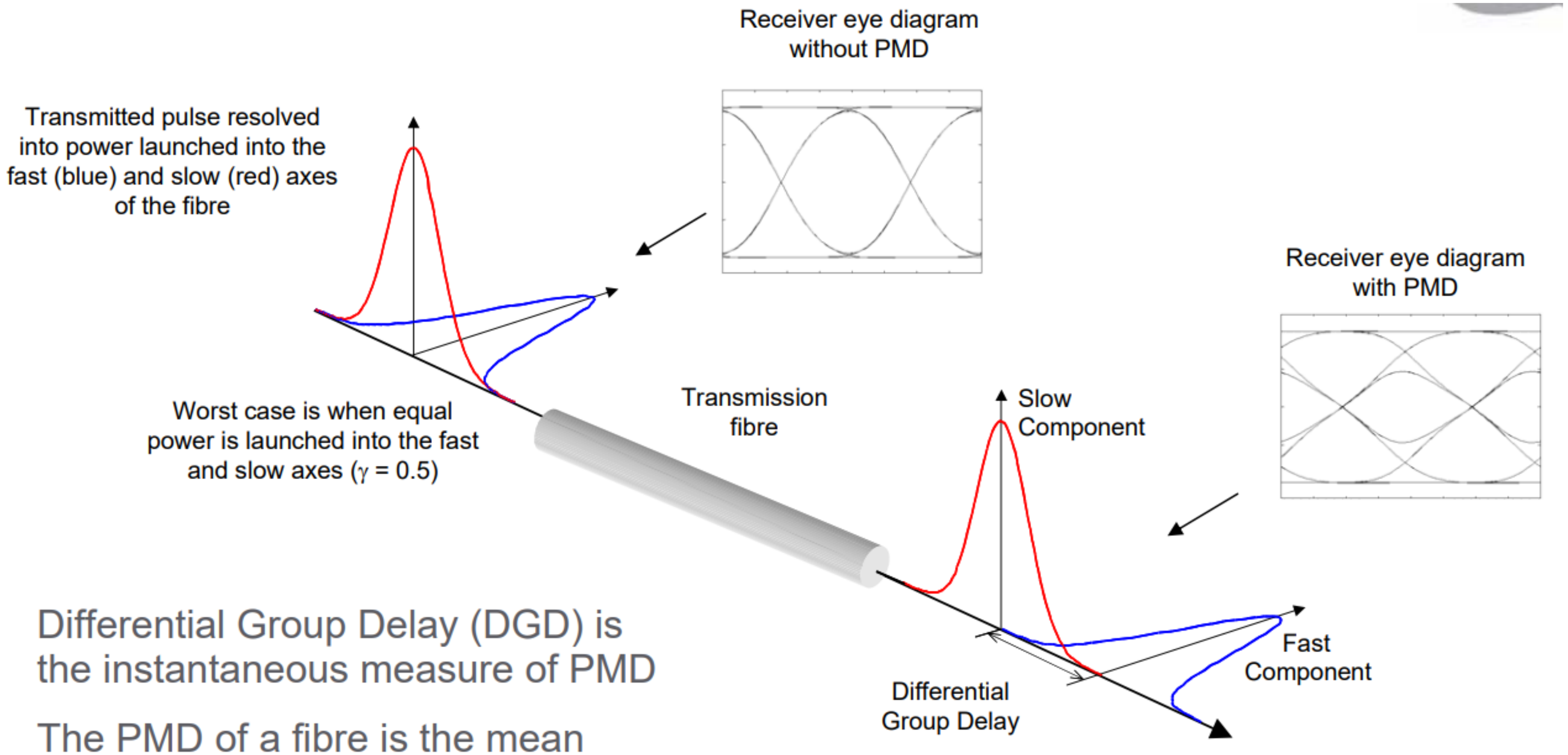
Cable PMD may become a constraint for 100 Gbaud systems and above

- 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



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

The PMD of a fibre is the mean value of DGD (<DGD>)

For IMDD Links less than 10km where *M=1*, Cable PMD can be derived from anslow_05_19

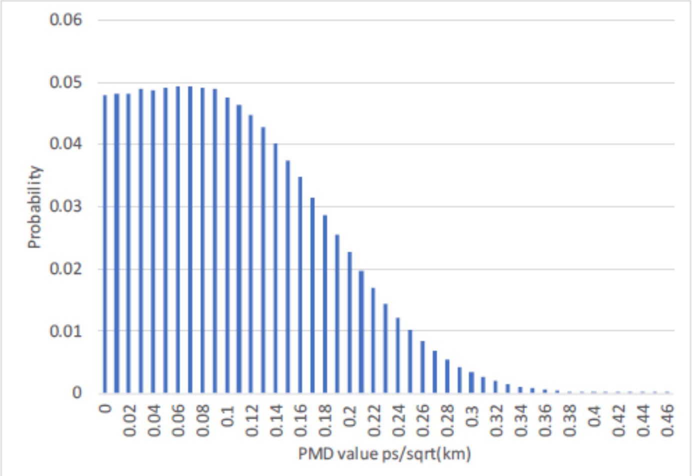
DGD_max 2

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

If the 10 km link is only 1 cable section, the probability of the PMD coefficient exceeding 0.43 ps/√km is 0.012%.

0.43 ps/√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 ps/√km would also apply for a 1 or 2 km link where M=1

Note: The ITU-T G.652 specification is 0.20 ps/√km, not 0.2 ps/√km as referenced above

A Mean Normalized PMD_Q example has been added to ITU-T G.652 Appendix I to predict 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 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 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 Mote Carlo simulation to derive 50,000 links with the fixed *M*.
  4) Derive the PMD_Q at Q=0.01.

Table I.6 Example dependence of mean normalized PMD_Q and mean normalized DGD on the number of concatenated cable pieces *M.*

Number of concatenated cables *M*	Mean normalized 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 $PMD_Q = 1.646 \times M^{-0.163}$
- This equation can be used to calculate the mean normalized PMD_Q at other values of *M* and multiplied by 0.20 ps/√km to calculate PMD_Q values at the ITU-T G.652 specification level of 0.20 ps/√km .
- For example, for *M=16*, Mean normalized PMD_Q = 1.646 X $16^{-0.163}$ = 1.05; PMD_Q = 1.05 x 0.20 ps/√km = 0.21 ps/√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 ~ 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 ~1 minute, and the mean time between excursions is ~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 ~ 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_B) 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_B) * (1/Ratio of Max to Mean (S)) * T_B

Allowable % T_B (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/√km) for IMDD links from 1 km to 100 km compared to cable PMD_Q

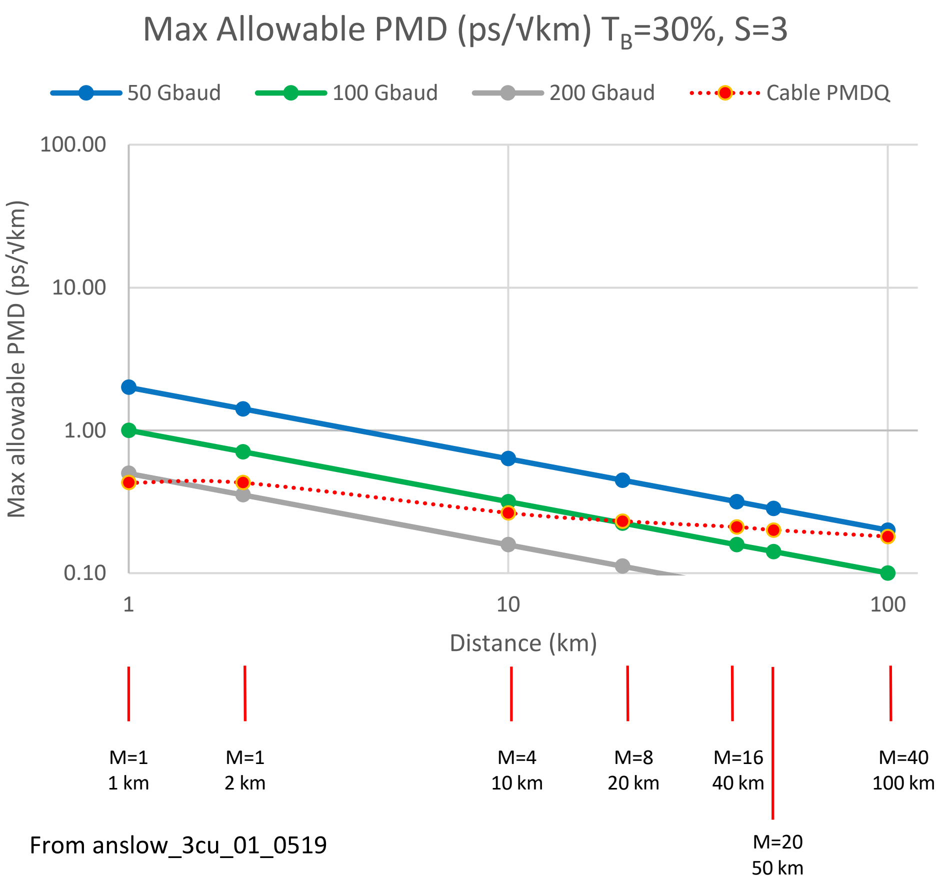
(This table is better described in the graphs on the following slides)

	Distance (km)	1	2	10	20	40	50	100
T_B= 30%	50 Gbaud	2.00	1.41	0.63	0.45	0.32	0.28	0.20
S= 3	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_Q	0.43	0.43	0.26	0.23	0.21	0.20	0.18
	Distance (km)	1	2	10	20	40	50	100
T_B= 30%	50 Gbaud	1.60	1.13	0.51	0.36	0.25	0.23	0.16
S= 3.75	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_Q	0.43	0.43	0.26	0.23	0.21	0.20	0.18
	Distance (km)	1	2	10	20	40	50	100
T_B= 26%	50 Gbaud	1.73	1.23	0.55	0.39	0.27	0.25	0.17
S= 3	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_Q	0.43	0.43	0.26	0.23	0.21	0.20	0.18
	Distance (km)	1	2	10	20	40	50	100
T_B= 26%	50 Gbaud	1.39	0.98	0.44	0.31	0.22	0.20	0.14
S= 3.75	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_Q	0.43	0.43	0.26	0.23	0.21	0.20	0.18

1. Cable PMD_Q was calculated using the recently added to ITU-T G.652 mean normalized PMD_Q 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.

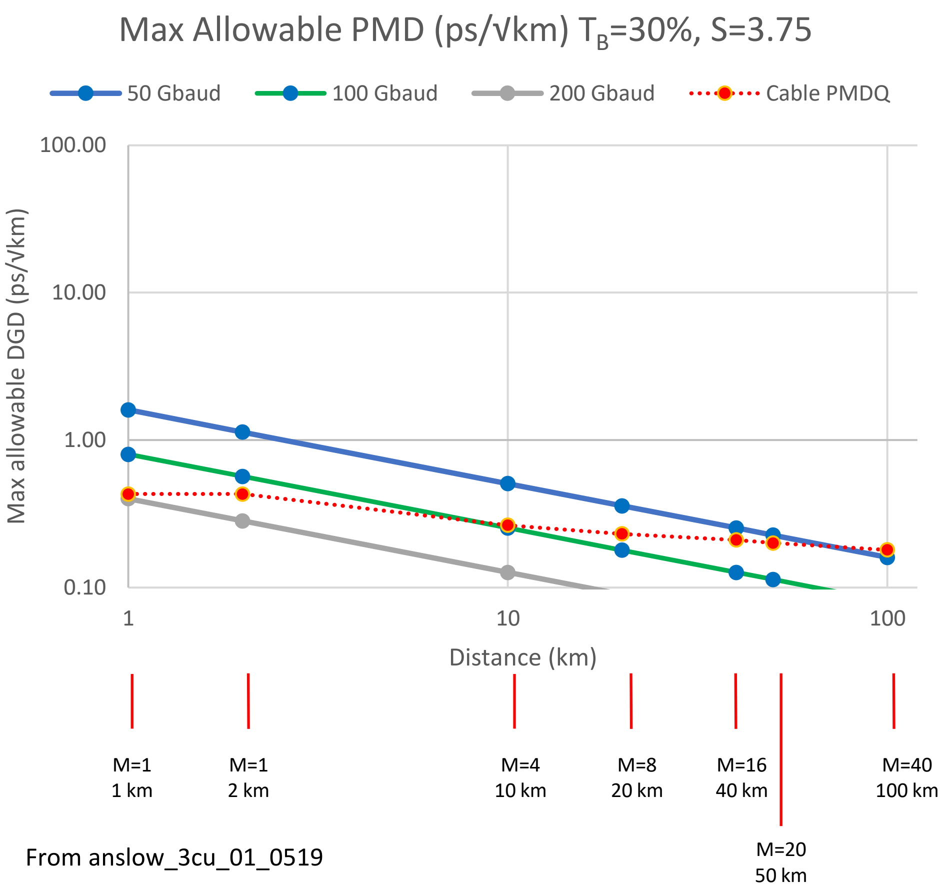
Max Allowable PMD (ps/√km) Scenarios for 1 dB Penalty

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



From anslow_3cu_01_0519

From ITU-T G.652 Appendix I

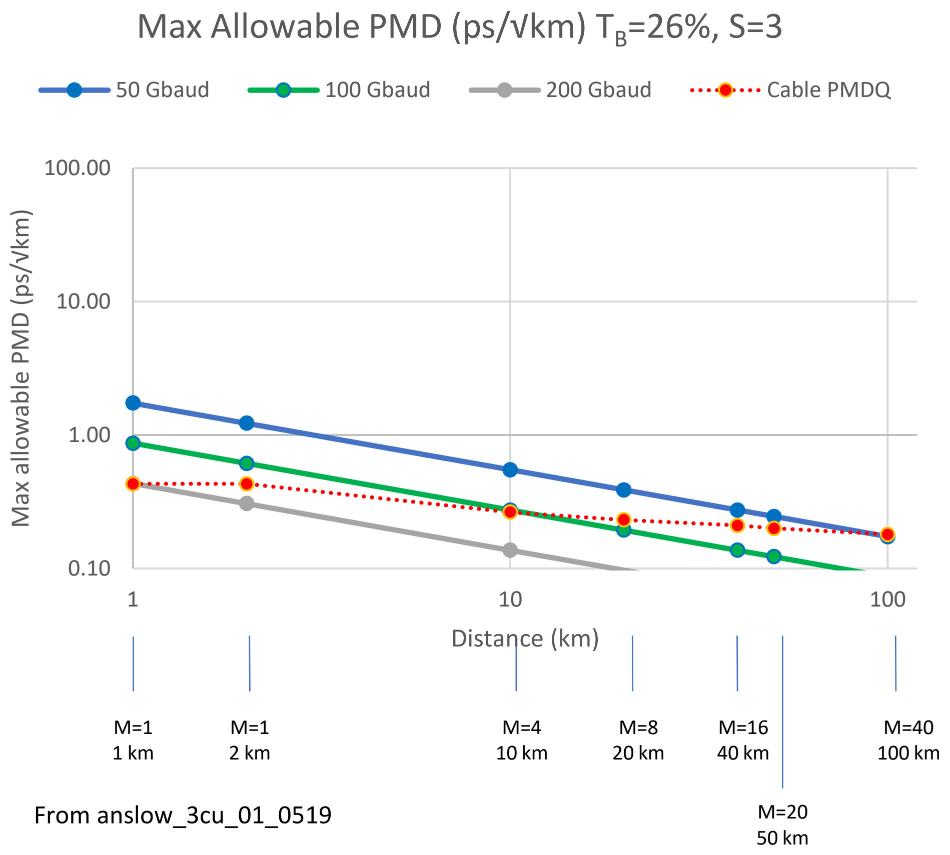


From anslow_3cu_01_0519

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



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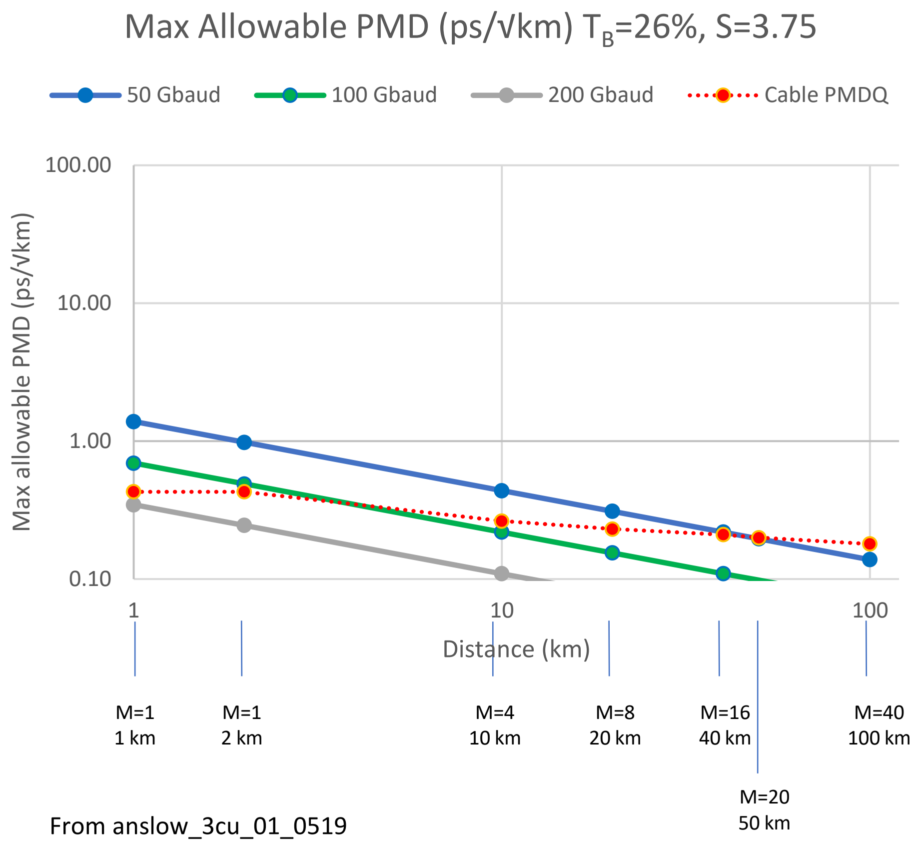
From ITU-T G.652 Appendix I



From anslow_3cu_01_0519

From ITU-T G.652 Appendix I

Max DGD using 3.75 ratio can be calculated from PMD_Q

- Max DGD (ps) = PMD_Q * √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