Polarization Mode Dispersion Aspects for Parallel and Serial PHY

IEEE 802.3 High-Speed Study Group

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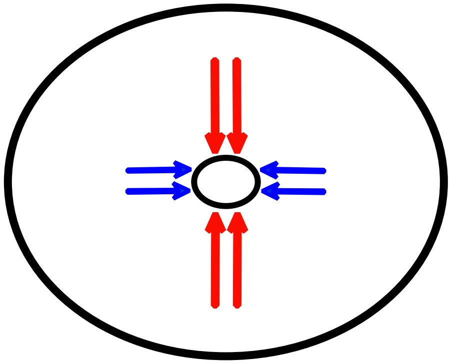
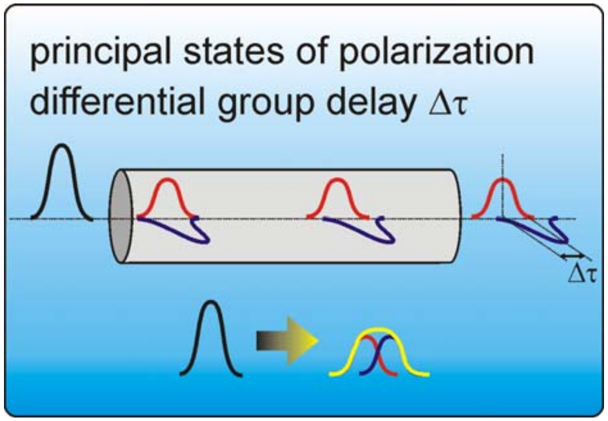
Outline

- What is Polarization Mode Dispersion (PMD) ?
- Probability of System Outage
- PMD-Limited Transmission Reach
  - Typical Fiber PMD-Coefficients
  - PMD Tolerance for Various Modulation Formats
  - PMD-Limited Reach for 100G Parallel & Serial PHYs
  - PMD-Limited Reach at Various Bit Rates
- Conclusions

Polarization Mode Dispersion (PMD)

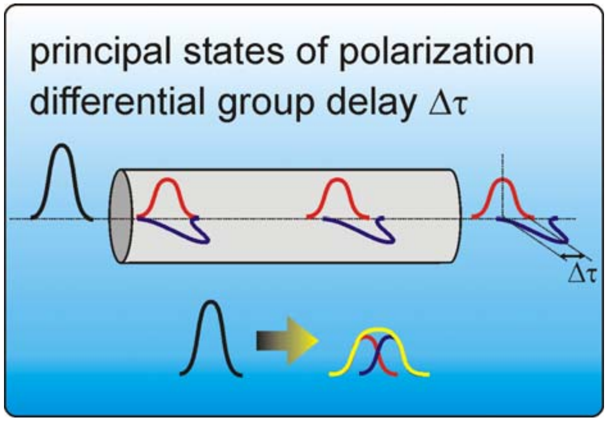


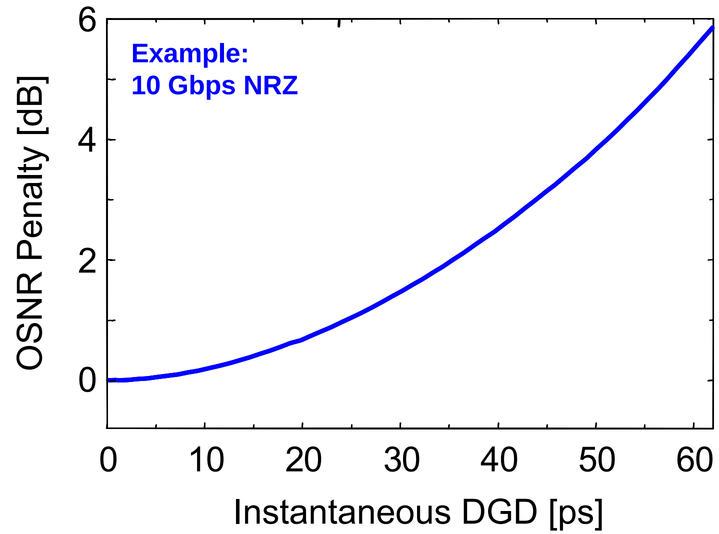


- Optical fiber is slightly **birefringent** (= different refractive indices for two orthogonal polarizations propagating in the fiber)
  - Manufacturing imperfections (deviations from perfectly cylindrical geometry)
  - Mechanical stress due to bending, twisting, spooling, cabling, etc.
- Fiber birefringence leads to **Polarization Mode Dispersion (PMD)** (= different speed of propagation between polarization components of a signal in the fiber)
- **First-order PMD** is characterized by the **Differential Group Delay (DGD)** between light traveling in the fiber's two eigen-polarizations
- **Higher-order PMD** describes the wavelength dependence of PMD. (In the absence of PMD compensation (PMDC), first-order PMD typically dominates.)

Reference [1,2]

PMD Leads to Transmission Penalties

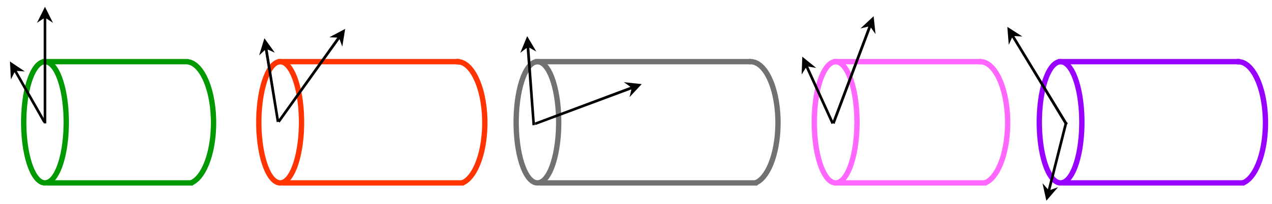




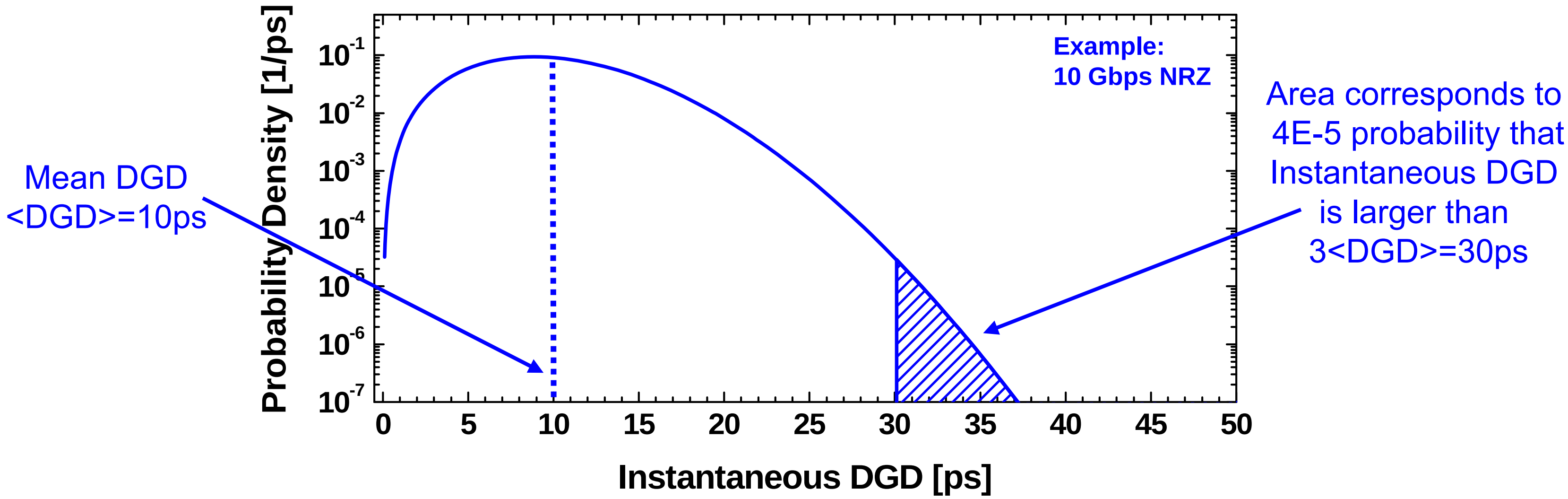
- Direct-detection receivers are **polarization insensitive** (optical power detection)
- First-order PMD manifests itself in echo-like **pulse broadening** after detection
- Broadened pulses spread into each other → **Transmission penalty**
- Amount of penalty depends on
  - Ratio of DGD to modulation symbol rate
  - Splitting ratio of pulse between fiber's two eigen-polarizations
  - Modulation format, receiver type, receiver characteristics, …
- **First-order PMD tolerance scales linearly with bit rate**

Reference [1,2]

PMD is a Random Phenomenon



- Birefringence varies randomly along a fiber. Long fibers can be modeled as a concatenation of short birefringent sections with random orientations.
- Two important consequences:
  1. The **instantaneous DGD** is a random quantity with **Maxwellian[1] probability density**
     → **There is always a finite probability to observe very high DGD values !**



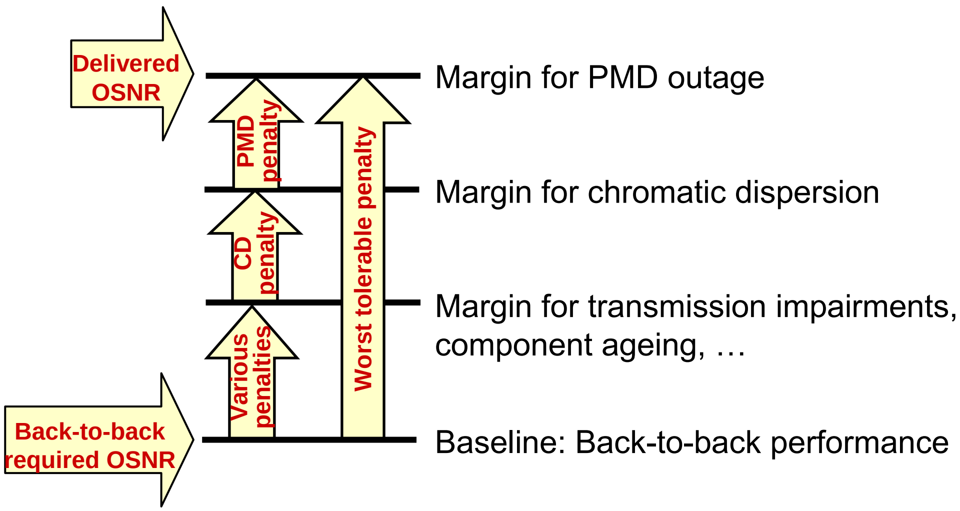
  2. The **mean fiber DGD** (<DGD>) scales with the **square-root of distance**

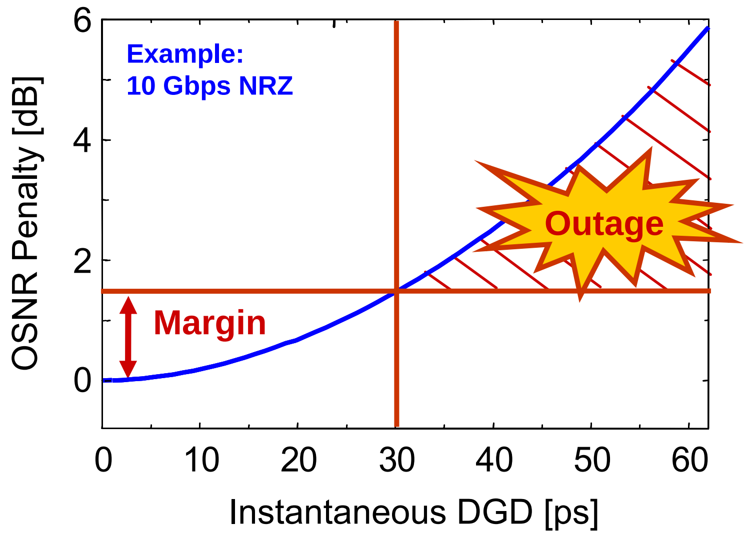
$$\langle DGD \rangle = \text{PMD-coefficient} \times \sqrt{L}$$

1: While Maxwellian DGD statistics are most commonly used, other statistics are also being considered, particularly in the presence of buried fiber plant [3,4]

PMD Can Lead to System Outage

Margin allocation in optical transport systems:





OSNR: Optical signal-to-noise ratio

Example: 30 ps instantaneous DGD leads to 1.5 dB OSNR penalty
→ With 1.5 dB margin allocated for PMD, the system can handle instantaneous DGD up to 30 ps
→ If more than 30 ps DGD happens to occur in this system: Margin is exhausted
→ System outage for the period of time where DGD > 30 ps

With what probability does this occur ? → Maxwellian statistics for DGD!

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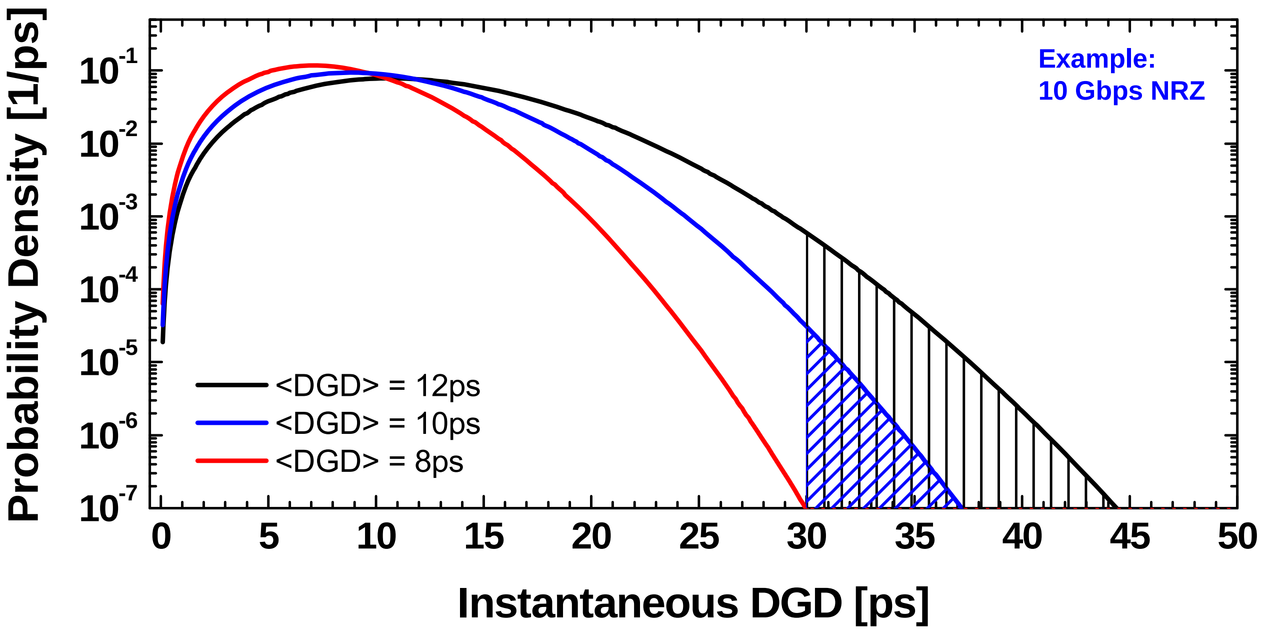
Mapping Instantaneous DGD to <DGD>



- Probability density function is Maxwellian (see backup)
- Outage probabilities are indicated by shaded areas (for a tolerable instantaneous DGD of 30ps for 1.5dB margin)
- Example: 30 ps instantaneous DGD tolerance corresponds to outage probability of
  - 7.8E-8 for 8ps mean DGD
  - 4.0E-5 for 10ps mean DGD ← 4.0E-5 frequently found number
  - 1.2E-3 for 12ps mean DGD
- Question: What is the acceptable outage probability for Higher-Speed Ethernet Systems ?

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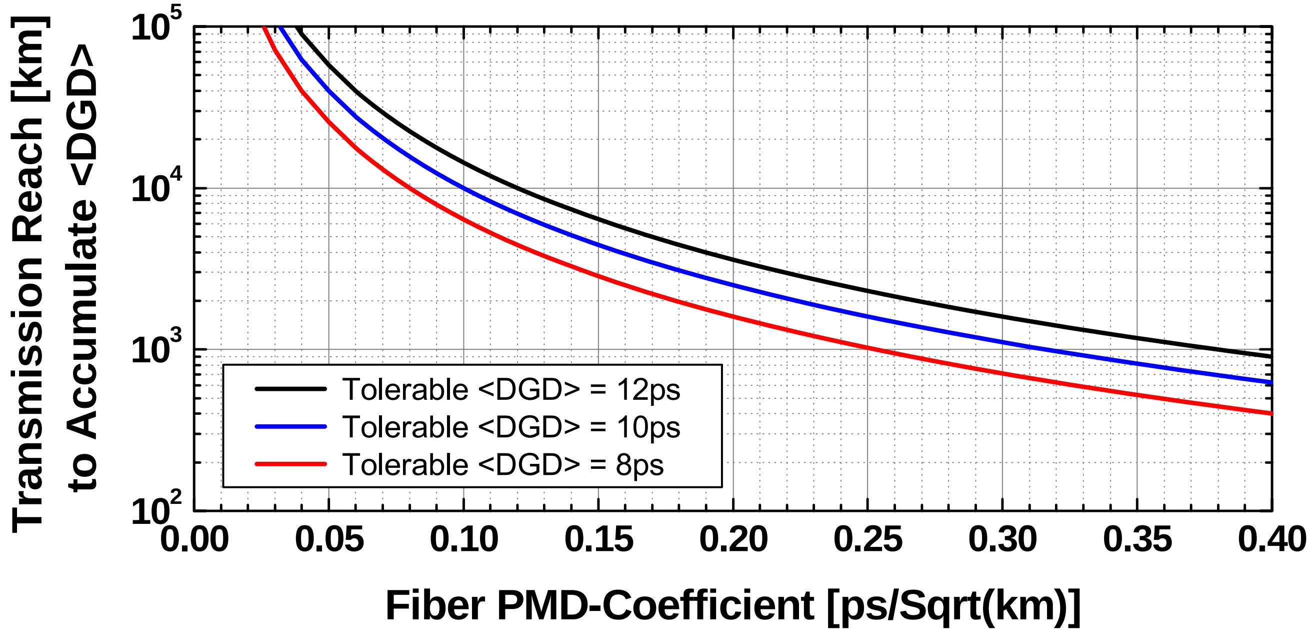
Mapping <DGD> to Transmission Reach



- PMD-limited transmission reach

$$L_{reach} \propto \langle DGD \rangle_{tol}^{2} \times PMD_{fiber}^{-2}$$

scales with square of tolerable <DGD> (tolerable <DGD> scales linearly with symbol rate) and with inverse square of (fiber) PMD-Coefficients

- Question 1: What are typical values for fiber PMD-Coefficients ?
- Question 2: How much DGD or <DGD> is acceptable for which modulation format ?

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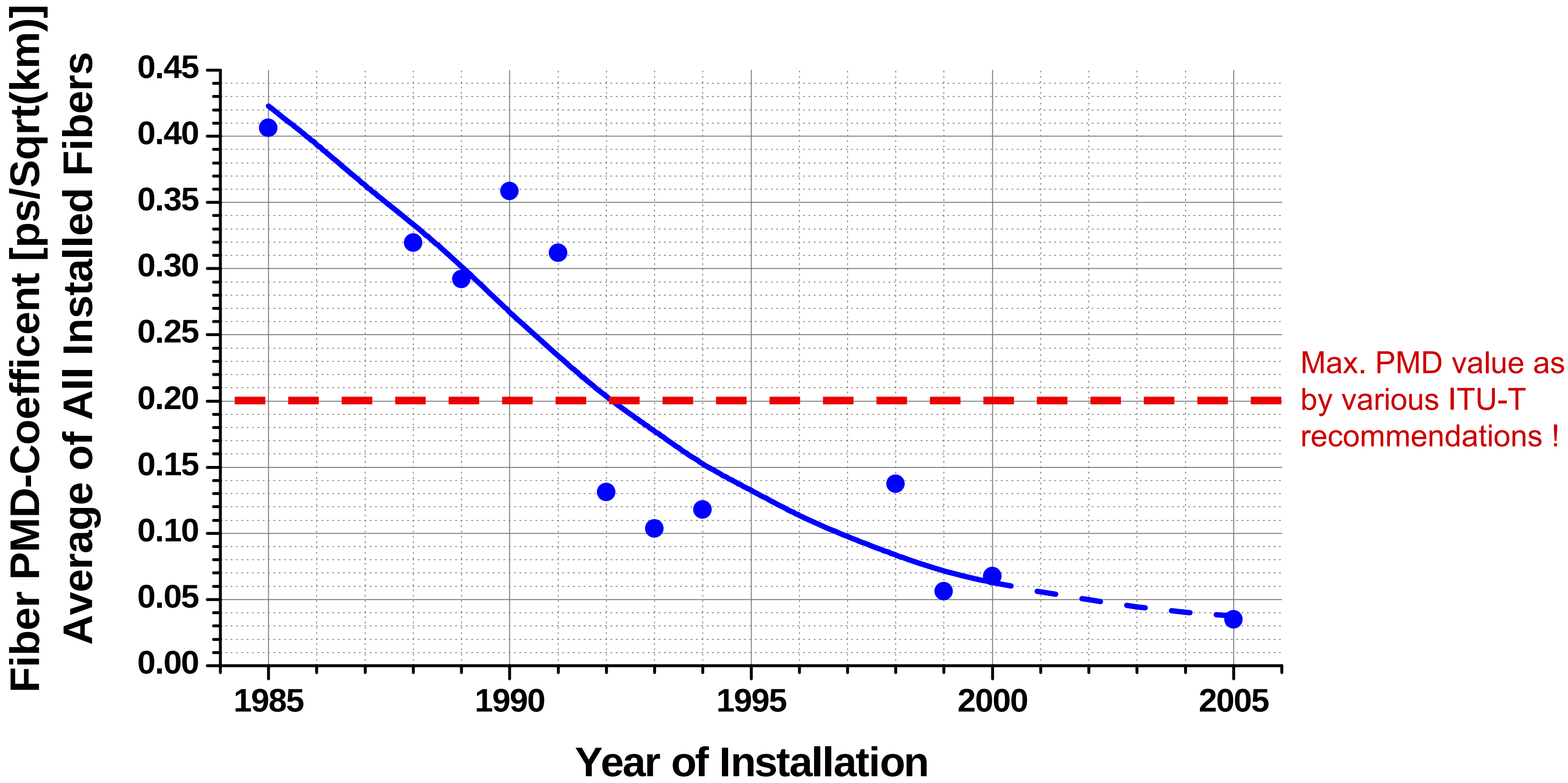
ITU-T's Recommendations for Max. PMD

- ITU-T specifies several fiber attributes, including maximum PMD values, for various optical fiber types, for example:
  - G.652 = Standard Single-Mode Fiber (SSMF)
  - G.653 = Dispersion-Shifted Fiber (DSF)
  - G.654 = Cut-off shifted fiber
  - G.655 = Non-Zero Dispersion-Shifted Fiber (NZDSF)
  - G.656 = NZDSF for wideband optical transport
- All of these above recommendations specify for long-haul or high bit rate transmission applications of 10-40 Gbps, including 10 GbE, a **maximum PMD coefficient of 0.20 ps/Sqrt(km)** for the fiber, for example
  - G.652.B/D
  - G.653.B
  - G.654.B/C
  - G.655 C/D/E
  - G.656
- Some recommendations mention **"common typical values"**, particularly for 40 Gbps intermediate and long reach applications, of **0.10 ps/Sqrt(km)** for the fiber PMD value, for example G.652, G.653, G.655, etc.

PMD Values of Installed Fibers (Example)



- PMD measurements of 9,770 installed fibers in Deutsche Telekom's network (fiber vintage: 1985 to 2001)**
- Today's fibers typically have low PMD < 0.05 ps / km$^{1/2}$

** D. Breuer et al., *"Measurements of PMD in the installed fiber plant of Deutsche Telekom"*, LEOS 2003 Summer Topical on PMD, paper MB2.1

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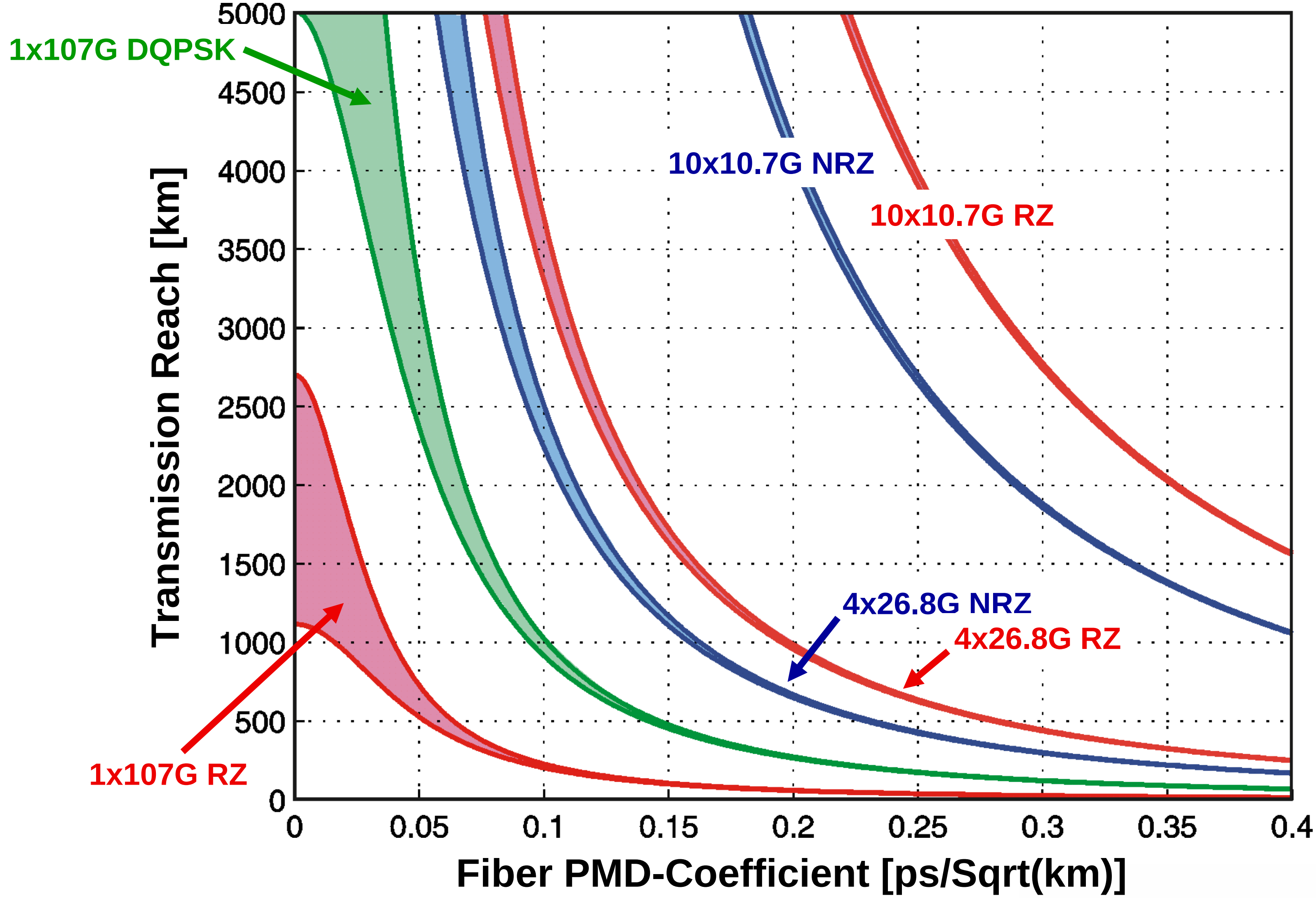
DGD Tolerance vs Modulation Format

Modulation Format	DGD (1.5 dB Penalty)	<DGD> (1.5 dB Margin, 4E-5 outage)
NRZ-OOK	41%	14%
RZ-OOK	51%	17%
Duobinary	30%	10%
NRZ-DPSK	47%	16%
RZ-DPSK	52%	17%
NRZ-DQPSK	101% **	34% **
RZ-DQPSK	108% **	36% **

- All data are simulated and hold for an OSNR-limited transmission system
- Measured data depend on exact pulse (eye) shape and receiver characteristics
- All <DGD> data given for 4E-5 outage probability → DGD = 3×<DGD>
- All data given for BER 1E-3 (FEC limit)
- All data given as percentage of the bit period !
- **: DQPSK has ~twice the PMD tolerance of DPSK because the symbol rate on line is reduced by half compared to binary signaling!

OOK = On-Off Keying
DPSK = Differential Phase-Shift Keying
DQPSK = Differential Quadrature Phase-Shift Keying
NRZ = Non-Return-to-Zero
RZ = Return-to-Zero (here: 50% duty cycle)

PMD-Limited Reach for 100 Gb/s + FEC



For 4E-5 Outage Probability and BER 1E-3 (FEC assumed)
Range in Transmission Reach (shaded area) explained in backup

PMD-Limited Reach: Various Bit Rates

	NRZ	50% RZ (OOK or DPSK)	50% RZ DQPSK
10 Gbps	14,000-15,700 km	20,600-23,100 km	
12 Gbps	9,700-10,900 km	14,300-16,000 km	
20 Gbps	3,500-3,900 km	5,100-5,800 km	
25 Gbps	2,200-2,500 km	3,300-3,700 km	
40 Gbps	870-980 km	1,290-1,450 km	5,800-6,500 km
80 Gbps	220-245 km	320-360 km	1,450-1,620 km
100 Gbps	140-160 km	205-230 km	925-1040 km
120 Gbps	100-110 km	140-160 km	640-720 km

- Data for 4E-5 Outage Probability, BER 1E-3 (FEC limit), 7% higher line rate
- Data for 0.1 ps/Sqrt(km) fiber PMD-Coefficient
- Modern fiber have much lower PMD values
  → 107 Gbps DQPSK = 2,950-4,520 km PMD-limited reach @ 0.04 ps/Sqrt(km)
- More details on reach calculation in backup
- Most prominent formats highlighted in gray !

Conclusion

- PMD-limited reach for 100 Gbps DQPSK (serial PHY) is greater than 1,000 km
- 100 Gbps DQPSK is therefore suitable for regional / long-haul transmission applications
- Transmission systems that support 40 Gbps binary formats will also support 100 Gbps DQPSK format (in terms of PMD-limited reach)
- Open question for further study: What outage probability is acceptable for Higher-Speed Ethernet ?

Backup

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PMD Mitigation

- **Optical techniques**
  - PMD compensators at the receiver
    - Bit rate agnostic
  - In-line polarization scrambling in combination with FEC
    - Scrambling rate needs to match FEC burst error correction capabilities
- **Electronic techniques**
  - Ranging from simple Feed-forward equalizers (FFE) to Maximum-Likelihood Sequence Estimators (MLSE)
    - Products available at 10 Gb/s
    - Research prototypes for FFEs at 40 Gb/s
- **Tracking speed**
  - PMD dynamics can be at kHz rates

Maxwellian Distribution

$$\mathrm{PDF}[\mathrm{DGD}] = \frac{8}{\pi^2 \langle \mathrm{DGD} \rangle} \left(\frac{2\mathrm{DGD}}{\langle \mathrm{DGD} \rangle} \right)^2 \exp\left[- \left(\frac{2\mathrm{DGD}}{\langle \mathrm{DGD} \rangle} \right)^2 / \pi \right] \quad (\mathrm{DGD} > 0)$$

- PDF = Probability Density Function
- DGD = Instantaneous Differential Group Delay
- <DGD> = mean DGD
- The tail of the Maxwellian PDF is unbounded
  → arbitrarily high values of DGD may be encountered with some low, but finite probability !

<DGD> and PMD-Limited Reach

- Assuming various PMD contributions per span:
  - $<DGD>_{fiber}$ through transmission fiber
  - $<DGD>_{DCM}$ through dispersion compensating modules
  - $<DGD>_{comp}$ through other components
- Typical values for span length L:
  - $<DGD>_{fiber}^2 = L \times 0.04^2$ ps^2/km — for modern fibers
  - $<DGD>_{fiber}^2 = L \times 0.4^2$ ps^2/km — for old fibers
  - $<DGD>_{DCM}^2 = (L/6) \times 0.11^2$ ps^2/km — DCF-based for SSMF
  - $<DGD>_{DCM}^2 = (L/20) \times 0.11^2$ ps^2/km — DCF-based for NZDSF
  - $<DGD>_{comp}^2 \leq 0.1^2$ ps^2 per optical component, ~3 components per span
- PMD-Limited Reach L_{reach}:

$$L_{reach} = <DGD>_{tol}^2 \times L / \{<DGD>_{fiber}^2 + <DGD>_{DCM}^2 + <DGD>_{comp}^2\}$$

with $<DGD>_{tol}^2$ being the tolerable (for a given OSNR margin) accumulated mean DGD for the particular modulation format (and receiver) under consideration (see slide 10), span length L

Variations in PMD-limited transmission reach (slide 11) due to DCF-based dispersion-compensating modules (DCMs) for SSMF (longer DCF → more <DGD> → shorter reach) and NZDSF (shorter DCF → less <DGD> → longer reach) …

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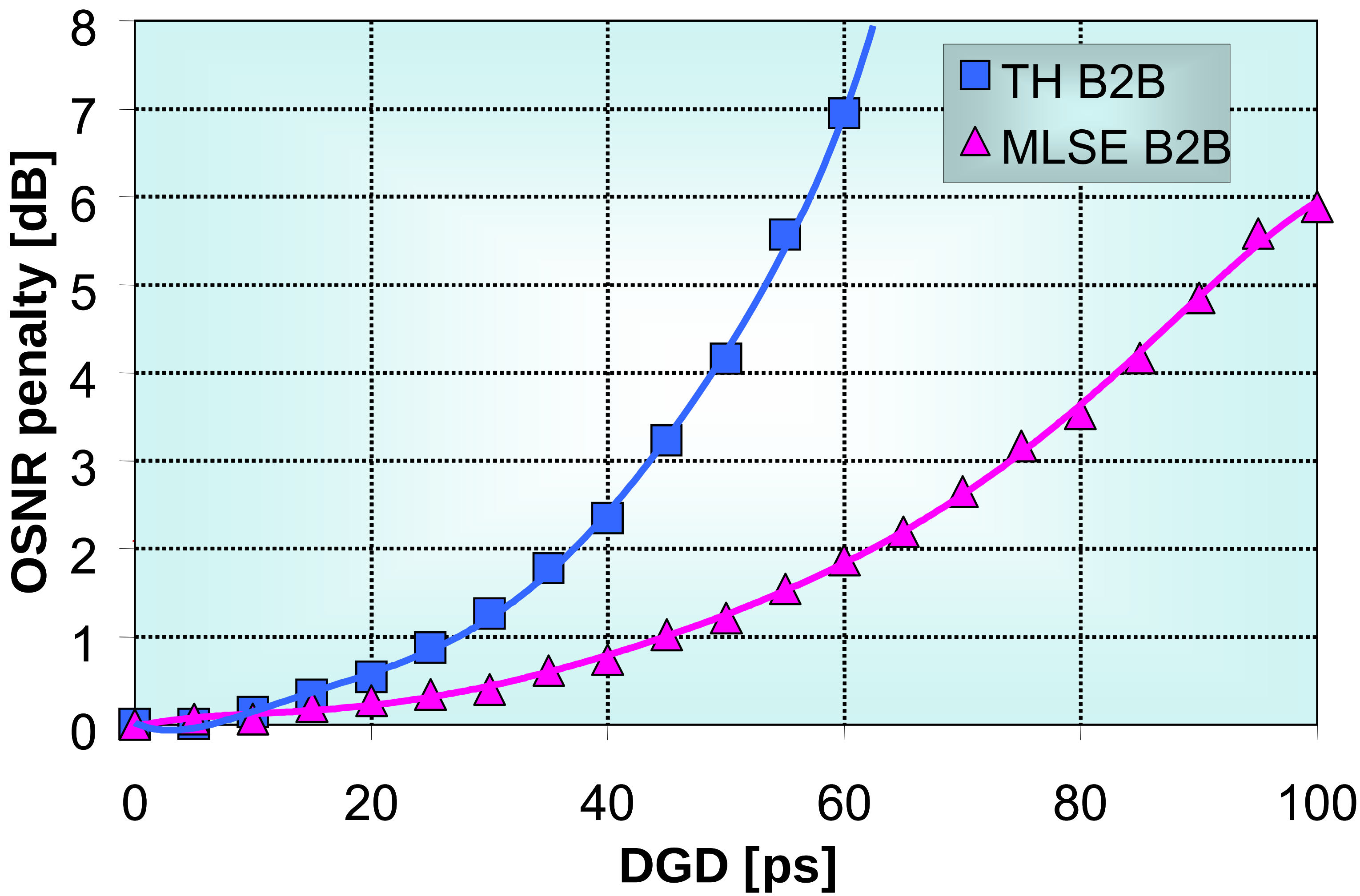
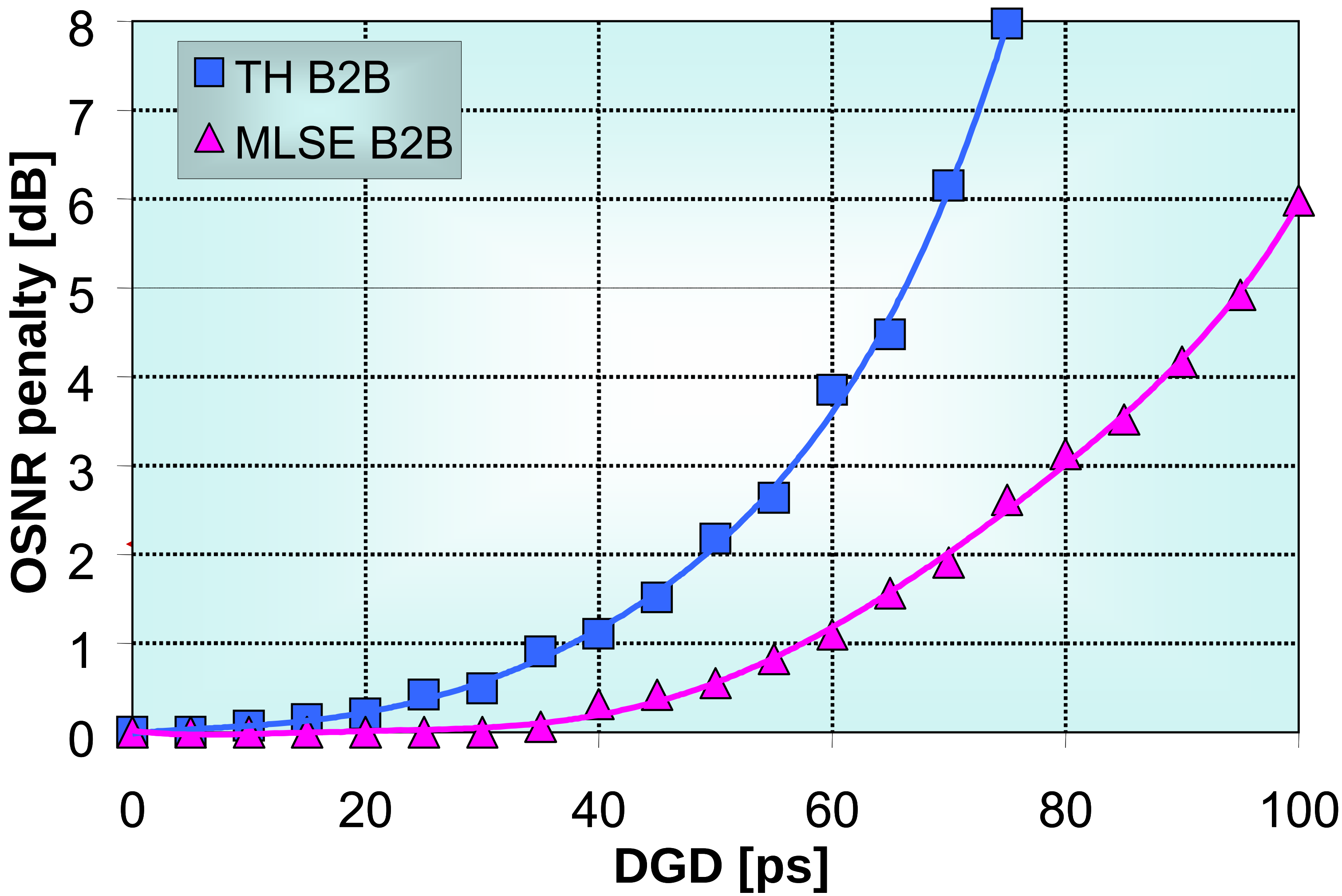
Measured PMD Tolerance, 10.7 Gb/s NRZ



Hard-Decision Receiver (TH), back-to-back, blue curve
Soft-Decision Receiver (MLSE), back-to-back, pink curve
Reference [5]

Measured PMD Tolerance, 10.7 Gb/s RZ



Hard-Decision Receiver (TH), back-to-back, blue curve
Soft-Decision Receiver (MLSE), back-to-back, pink curve
Reference [5]

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References

- [1] H. Kogelnik, R. M. Jopson, and L. E. Nelson, "Polarization-Mode Dispersion" in Optical Fiber Telecommunications IVB, I. Kaminov and T. Li (eds), Academic Press 2002.
- [2] C. D. Poole and J. Nagel, "Polarization Effects in Lightwave Systems", in Optical Fiber Telecommunications IIIA, I. P. Kaminov and T. L. Koch (eds), Academic Press 1997
- [3] M. Brodsky, M. Boroditsky, P. Magill, N. J. Frigo, and M. Tur, "Channel-to-channel variation of non-Maxwellian statistics of DGD in a field installed system," in Proc. European Conf. on Optical Communication (ECOC 2004), vol. 3, Paper WeI.4.1, pp. 306–309.
- [4] H. Kogelnik, P. J. Winzer, L. E. Nelson, R. M. Jopson, M. Boroditsky, and M. Brodsky, "Fist-Order PMD Outage for the Hinge Model", IEEE Photon. Technology Letters, vol. 17, no 6, 1208-1210 (2005).
- [5] J. M. Gene Bernaus, P. J. Winzer, S. Chandrasekhar, and H. Kogelnik, "Joint PMD and Chromatic Dispersion Compensation Using an MLSE", Proc. ECOC'06, We2.5.2 (2006).