PMD Performance Requirements in Optical Fiber Communication Systems

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PMD Fundamentals

The concepts of Polarization Mode Dispersion (PMD) and Differential Group Delay (DGD) are sometimes used interchangeably within the industry to describe the effect of an optical pulse spreading due to fiber birefringence. According to the IEC 60793-1-48 standard on PMD measurement methods and test procedures [1], “the term PMD is used both in the general sense of two polarization modes having different group velocities, and in the specific sense of the average DGD value.” The latter definition comes from the fact that in an optical fiber, the random nature of the orientation of light launch conditions and coupling within the given fiber section, as well as fiber bends and twists result in a fluctuating DGD. Random time-dependent temperature and mechanical perturbations enhance these DGD fluctuations further. Put differently, if one were to measure the DGD at the output of the fiber repetitively, they would observe that DGD is a random value that follows a certain distribution. The PMD is often defined as the average DGD within that distribution. Another mindset, currently prevalent in the industry to differentiate the notions of PMD and DGD, is to view PMD as a fiber-related attribute and DGD as a system-related attribute. Hence, some often view DGD as the cumulative amount of PMD-induced pulse spreading after transmission over multiple concatenated fiber sections that comprise of different PMD values.

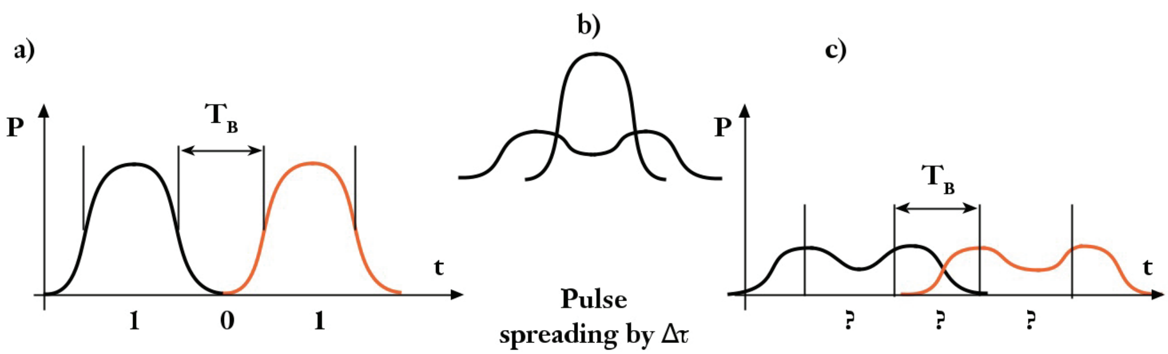

Figure 1. Qualitative illustration of PMD-induced transmission impairment
(a) The shape of the original pulse sequence where each pulse occupies a designated bit slot (b) Spreading of the pulse due to DGD (c) Shape of the overlapped pulses at the receiver where individual pulses have “leaked” out of their designed bit slots making it difficult for the receiver to decide whether it sees “1” or “0.”

The impact of PMD will ultimately manifest itself in the form of signal distortion, and the easiest way to visualize it is to consider intensity-modulated signals (see Figure 1). As the distance increases, the adjacent pulses start to spread, their amplitude gets reduced, and tails starts to overlap. The distortion arises when the time slot (or a bit period, T_B) of an individual pulse is stretched by the PMD-induced delay to the point where the tail-end of a leading pulse overlaps with the leading edge of a subsequent pulse. Therefore, it is more likely to observe higher DGD at the receiver over longer distances.

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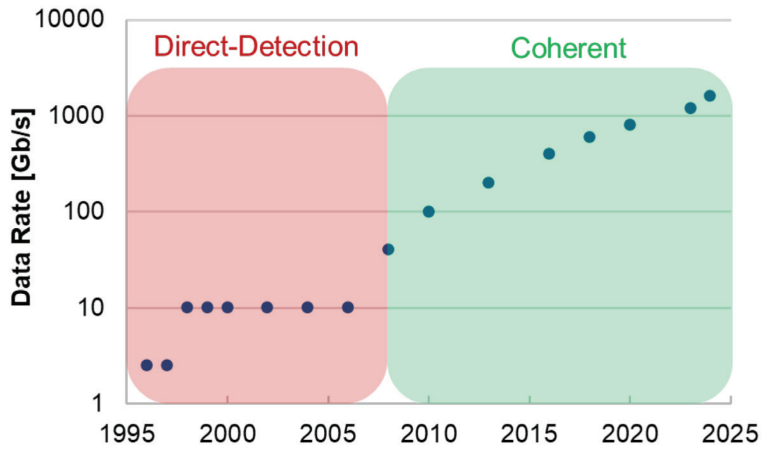

Figure 2. Evolution of active long-haul equipment data rates per wavelength

In networks employing amplitude-modulated transmission based on direct detection, PMD has historically been a difficult impairment to compensate. Many techniques were proposed in research but were never integrated into real networks. As the impact of PMD worsens with the data rate, the industry was led to believe that many networks would struggle with upgrades to data rates beyond 10 Gb/s [2]. However, the advent of systems with coherent detection for medium and long-reach transmission unlocked (perhaps somewhat unexpectedly) an ability to compensate for a much larger amount of PMD, compared to its direct-detection counterparts. As a result, the impact of transmission impairments that were historically associated with PMD has been significantly reduced. As of today, transponders used in core networks continue to be based on coherent detection, with 100-800 Gb/s representing the largest share of all units sold today, and 1.2-1.6 Tb/s transmission systems are on the horizon [3-6] (see Figure 2). Those transponders are designed to have a certain specification for maximum allowable DGD, which typically varies between 100 and 160 ps [7,8], and there has been experimental demonstration of even higher (500 ps) DGD tolerance [9]. For coherent pluggables, the maximum allowable DGD is also specified at 100 ps [10]. Some transponders also have a specification for mean DGD [7].

These two (mean and maximum) DGD specifications stem from the fact that the expected DGD at the end of the link follows a certain distribution, as described earlier. Numerous experiments and theory revealed that DGD histograms could be well approximated by a Maxwellian probability distribution [1]. The DGD distribution has a mean DGD associated with it, and a maximum DGD that is defined as the value at which there is a 99.99% probability that the actual link DGD will be below that value. The nature of Maxwellian distribution means that the maximum DGD is 3 times higher than the mean DGD value, which simplifies the conversion between the two DGD values – an example of such a distribution is shown in Figure 3.

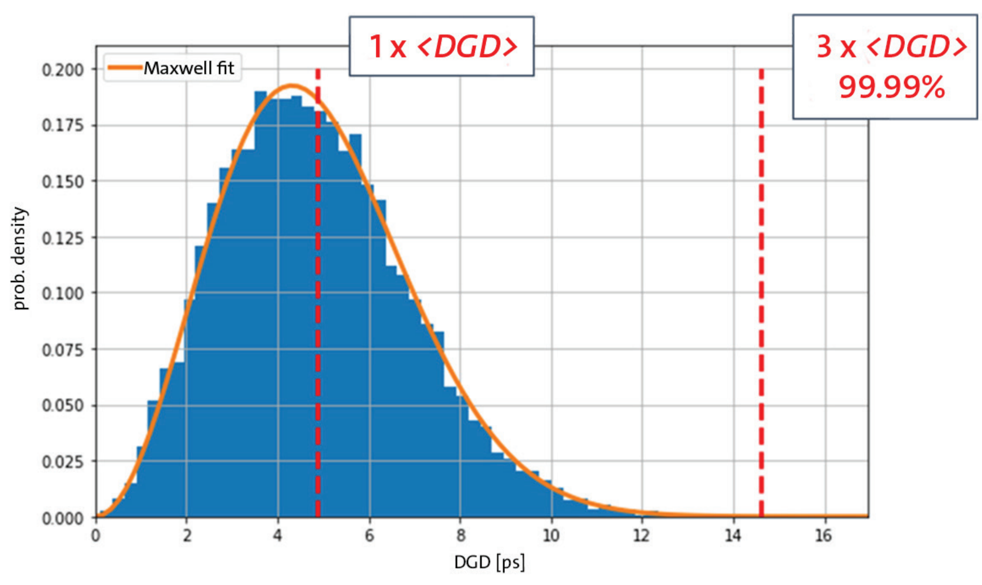

Figure 3. An example of transmission link DGD distribution

As with all other fiber parameters, there is a certain distribution of PMD across individual fiber spools during fiber production, which poses the question of how PMD should be specified by a fiber manufacturer. Over the years, the concept of a PMD_Q has been the preferred specification method. PMD_Q is defined as a statistical upper bound for the PMD coefficient of the concatenated optical fiber cables within defined possible links of M sections. The upper bound is defined in terms of a small probability level, Q, which reflects the probability that a concatenated PMD coefficient value exceeds PMD_Q [11,12]. In both ITU-T Recommendation G.652 and G.654 standards, M and Q are equal to 20 and 0.01%, respectively, and the most commonly used maximum PMD_Q value for cabled fiber is 0.20 ps/√km. Simply put, this ensures with 99.99% probability that the PMD value of 20 or more concatenated cabled fiber sections is ≤0.20 ps/√km. Cabled PMD_Q is considered to be a more representative parameter to use for an expected link design PMD compared to a mean or maximum PMD fiber value. It is also important to note that cabled fiber may have different PMD distribution as compared to un-cabled fiber given contact with other fibers and protective jacket materials (i.e. potential for stress-induced birefringence).

Impact of PMD on Transmission Performance

Coherent Systems

PMD_Q can be converted into DGD (mean) and DGD (max) using the formula below:

$$DGD_{max} = 3\langle DGD\rangle = 3\sqrt{\sum_{N_s} PMD_i^2 \cdot L_i} = 3\sqrt{L} \cdot PMD_Q \quad (1)$$

In this formula, PMD_i is the PMD of any given individual fiber section, L_i – associated length of each section, N_s – number of fiber sections, and L – is the total length of the transmission link. This formula allows us to calculate the maximum allowable cabled fiber PMD_Q value, i.e., the value at which the total accumulated link DGD remains within the active equipment DGD compensation capability. Figure 4 shows that the maximum allowable PMD_Q for coherent transponders and coherent pluggables (capable of compensating a total of 100 – 150 ps maximum DGD, as discussed earlier) is higher than 0.20 ps/√km across all distances. This suggests that the maximum PMD_Q of 0.20 ps/√km (as specified in the ITU-T standards) is fully compliant with the DGD capability of today's coherent transponders and coherent pluggables across a wide range of distances. These calculations confirm that the maximum cabled fiber PMD_Q value of 0.20 ps/√km remains an appropriate PMD specification for a wide range of networks that use coherent transponders or coherent pluggables.

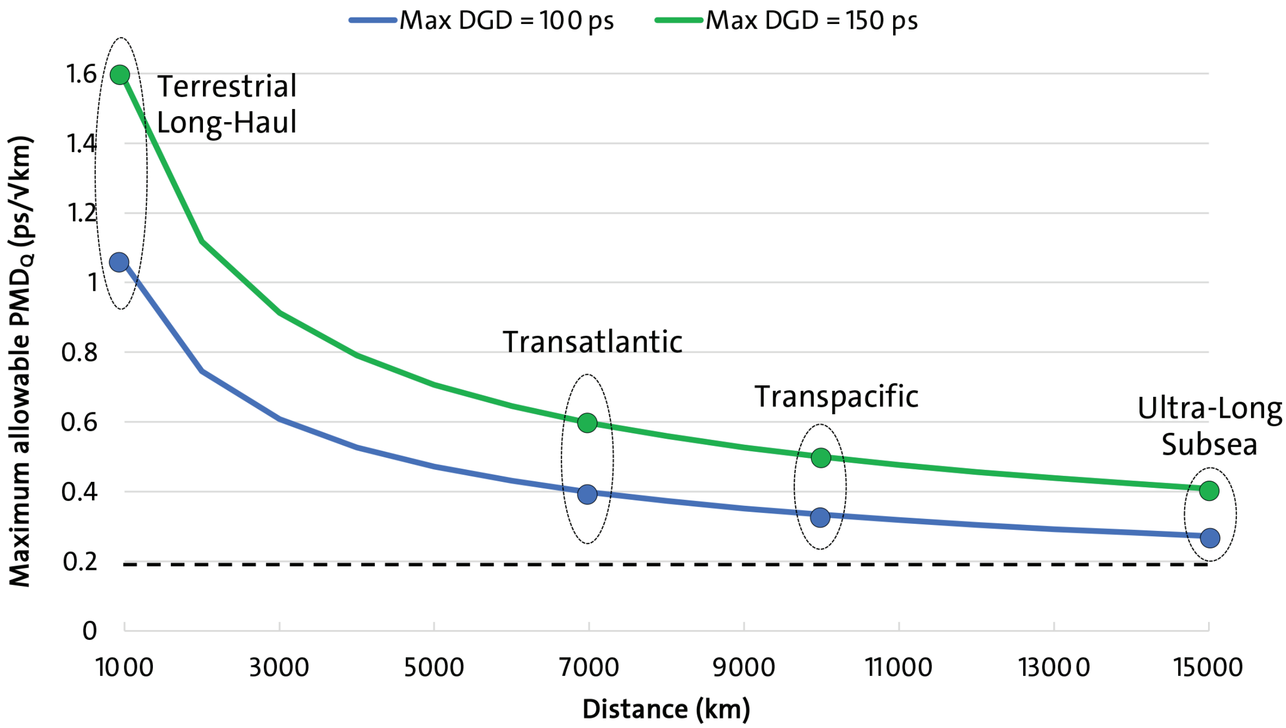

Figure 4. Maximum PMD_Q for different distances and equipment DGD compensation capabilities

Non-Coherent (Direct-Detection) Systems

In short-reach systems, most of which are still based on direct-detection transceivers, PMD remains an important factor, which could potentially limit transmission performance. In those systems, the general rule is that the maximum DGD-induced penalty of 1 dB is acceptable, and this amount of penalty occurs when the DGD reaches 30% of the bit period [13 – page 29]. If one wants to ensure that the probability of the DGD of the fiber link exceeding DGDmax is less than 4.2×10^{-5}, the link must be designed with a DGD that is one third of the DGDmax [13 – page 11], with the DGDmax being only 30% of the bit period (T_B). The cited probability of 4.2×10^{-5} equates to the 99.99% probability (rounded down to the nearest decimal point) that the link DGD remains equal to or below the DGDmax. These probability values are widely seen as appropriate within the industry and ensure the best balance between minimizing PMD-induced impairments and avoiding link over-engineering. This yields the rule often used in the industry to determine the maximum allowable link DGD:

$$DGD < 0.3 \times (1/3 \times T_B) = T_B/10 \quad (2)$$

Therefore, one can determine the maximum allowable cabled fiber PMD for any given baud rate and transmission distance (Figure 5).

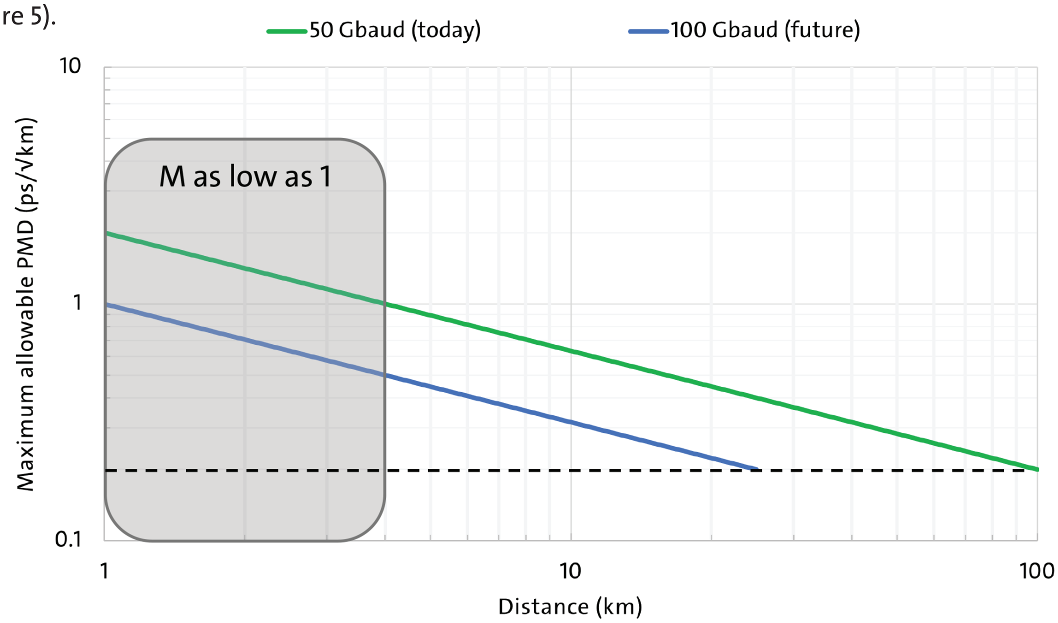

Figure 5. Maximum allowable PMD and transmission distance for different transceiver technologies

In legacy on-off keyed (OOK) systems, where the signal can only take one of the two states at any point in time (“1” and “0”), one usually refers to the bit rate to determine the overall speed of transmission. In today’s systems, however, this is no longer adequate as signals are often more complex and contain multiple amplitude and/or phase levels. By contrast, the baud rate is agnostic to any particular signal shape and is, therefore, a more representative metric to define the time between the two consecutive signals (i.e., bit period, T_B). The state-of-the-art 400 Gbit/s non-coherent PAM-4 transceivers used today operate at 25 or 50 Gbaud, which corresponds to the bit period of 40 or 25 ps, respectively. It is widely expected that future PAM-4 transceivers will evolve towards 100 Gbaud, thus, reducing the bit period to 10 ps. This translates to the maximum allowable link DGD of 1 ps (Formula 2) and the maximum length of 25 km, assuming cabled fiber PMD value of 0.20 ps/√km (Formula 1). These calculations confirm that even with the next-generation transceivers likely operating at 100 Gbaud, the achievable distance will still serve the needs for on-campus data center interconnects and most access networks.

We note that when it comes to cabled fiber PMD specification for very short-reach (1 – 4 km) non-coherent systems, it seems more logical to specify the maximum allowable PMD value of each individual cable section, since those applications may only require a single cable section (M = 1). As a result, in those scenarios the concept of PMD_Q may not be applicable since the very definition of PMD_Q is based on having at least 20 cable sections (M = 20) in today’s ITU-T G.652 Recommendation. Figure 5 shows that one can tolerate a much higher PMD (0.50 - 1 ps/√km) even for a future 100 Gbaud PAM-4 transceiver if a link consists of a single 1 - 4 km cable section. By contrast, as the transmission distance (and number of spliced cable sections, M) increases, the PMD_Q metric starts to matter more.

The Impact of Fast SOP Rotations on System Performance

After several years of initial successful operation of coherent systems, an issue affecting transmission over Optical Ground Wire (OPGW) cables was discovered. This issue manifested itself through a sudden and significant increase in the number of transmitted bit errors, leading to a total system failure for short periods of time. This phenomenon was observed on a seasonal basis, and initially could not be explained using conventional means. It was, however, hypothesized (and later proven) that the issue takes place when an OPGW cable is struck by lightning, which creates much faster-than-normal State of Polarization (SOP) rotations. It has been reported that under normal operating conditions of terrestrial cables, SOP rotations of up to 20 krad/s were observed, while some of the strongest lightning strikes can cause the SOP rotations of more than 2 Mrad/s [14]. It became apparent that the Digital Signal Processing (DSP) within a coherent transponder was simply not designed to withstand these super-fast SOP rotations. The nature of this phenomenon is now clear: due to the presence of woven steel wires in the OPGW cable, during a thunderstorm a lightning strike forms a strong longitudinal magnetic field in the cabled fiber, the change of which leads to the fast SOP rotation and results in transmission errors on the receiving side (Figure 5).

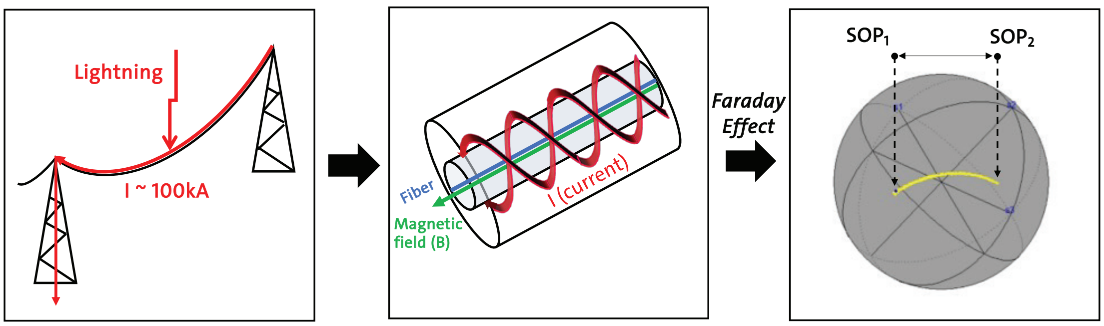

Figure 6. Principle of fast SOP rotation due to OPGW cable lightning strikes

Two remedies to this problem were proposed. First, active equipment manufacturers have updated their DSP capability to withstand the SOP rotations of up to 3-6 Mrad/s, which exceeds the maximum speed of SOP rotations from even the strongest lightning strikes [8,14,15]. The second solution was to provide modifications to the OPGW cable to reduce the amount of induced magnetic field. To the best of our knowledge, these concerted industry efforts provided an effective solution to avoid further optical transmission disruptions in the OPGW cables caused by lightning strikes.

Summary

This white paper summarized the fundamentals associated with the effect of PMD, and functional implications on transmission performance of short-, medium-, and long-reach transmission systems. For long-reach systems, the emergence of coherent technology provided a significant relief to the transmission impairments related to PMD, and further improvements along the way provided an even stronger protection against polarization-related effects (ex. fast SOP rotations). We do not expect that PMD will re-emerge as a severe impairment in those systems. For shorter systems, even with the next-generation non-coherent transceivers, the current cabled fiber PMD_Q specification in the ITU-T Recommendation G.652 standard yields a transmission distance of at least 25 km, which is within the reach requirements of on-campus DCI and most access networks.

The analysis presented in this white paper confirms that the current ITU-T G.652 and G.654 Recommendation maximum PMD_Q (M = 20, Q = 0.01%) specifications for cabled fiber ≤ 0.20 ps/√km remain fit for purpose and are compliant with the active equipment DGD capabilities used in medium- and long-reach systems. We do note, however, that for short-reach non-coherent systems (consisting of one or few cable sections), a maximum individual cabled fiber PMD value may be a more appropriate metric for establishing the PMD specification and an opportunity for continued work in industry standards.

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