# Do's and Don'ts for a Correct Nonlinear PMD Emulation in 100Gb/s PDM-QPSK Systems

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**Abstract**

In this paper we compare by numerical simulations different schemes to emulate the interaction between polarization mode dispersion (PMD) and nonlinear effects in 100Gb/s polarization division multiplexing quadrature phase shift keying (PDM-QPSK) transmission systems in laboratory experiments. We find that the correct choice of emulation scheme strongly depends on the characteristics of the line and, in general, emulating the PMD at the transmitter doesn't ensure a correct reproduction of the PMD/nonlinear effects interaction.

**Keywords:** Polarization mode disperion; Cross polarization modulation; Modulation formats; Coherent detection;

## 1 Motivation and Background

THE correct emulation of polarization-mode dispersion (PMD) has been the subject of theoretical and experimental studies for many years [1–3]. Today, PMD emulators are available as compact lab instruments. As long as single polarization, directly detected signals are considered, the distortion induced by linear PMD is one of the main sources of penalty. This is especially true at very high baudrates ($>$ 10Gbaud) [4], both for intensity modulated and phase modulated transmissions [5]. When PMD-induced linear distortion is dominant, the position of a PMD emulator in an experimental setup is indifferent, and the emulator is usually placed at the output of the transmitter or before the receiver for simplicity. However in transmission systems employing polarization-division multiplexing (PDM) and coherent detection, both the amplitude and the phase of the signal are available at the receiver. The linear PMD can be thus effectively compensated in the electrical domain using digital signal processing (DSP) algorithms [6]. In these systems, linear PMD is not a concern, even for extremely large values of differential group delay (DGD), while other polarization-related effects, like cross-polarization modulation (XPolM) [7–9], are major sources of penalty. These distortions are due to the interaction between PMD (or even simple birefringence) and Kerr effect and thus they are intrinsically nonlinear and distributed along the line [10].

A very practical problem when assessing through experiments the penalty induced by these distortions is that, while deployed fibers can have very large amounts of PMD, new generation fibers are typically used in the laboratories. These fibers have a very small PMD coefficient due to an improved production process and PMD should be somehow emulated in the experimental setup using polarization maintaining fiber (PMF) sections or appropriate devices composed of a number of programmable waveplates. In this scenario a correct emulation of the PMD-related

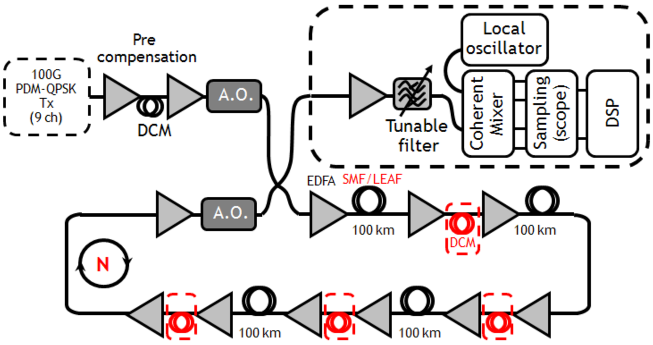


Figure 1: Basic simulative setup used in the simulations.

effects does not only depend on the characteristics of the PMD emulator, but also on its position in the experimental setup. It is thus interesting to analyze the impact of the line parameters (transmission fiber, dispersion management, etc.) on the accuracy of the PMD estimation, using different emulation schemes. Given that PDM quadrature phase shift keying (QPSK) is the format of choice for 100Gb/s long-haul transmissions, we focus on this format for our tests.

In this work we perform extensive simulations from which we derive some simple rules to be used in experimental investigations of PMD/nonlinear effects (NL) interactions in 100Gb/s PDM-QPSK transmission systems. Specifically, we estimate the probability density function (PDF) of the $Q^2$-factor for the selected configurations, comparing different emulation techniques with the real case of inline distributed PMD. This way it is possible to verify if the emulation schemes are able to capture the distributed nature of PMD/NL interactions. For this kind of work, numerical simulations provide a simple and reproducible testbed, not affected by the instabilities of a real lab recirculating loop.

This paper is organized as follows. In section 2 we describe the numerical setup used in the tests. Then in section 3 we present the results of the simulations. Finally in section 4 we discuss the main results and draw our conclusions.

## 2 Simulation Setup

In this section we describe in detail our simulations [11]. The basic setup is depicted in Fig. 1. We always test the central of 9 channels, all modulated with PDM-QPSK at 112Gb/s. The channels are spaced by 50GHz and modulated using random patterns [12]. We verified that further increasing the number of channels has a negligible impact on performance. The phase noise of the lasers is neglected and the input states of polarization (ISOP) of the channels are randomly selected over the Poincaré sphere at each run. The signal is then propagated over a recirculating loop composed of four 100-km spans of either non-zero dispersion shifted fiber (NZ-DSF, D=4ps/nm/km, S=0.085ps/nm$^2$/km, $\alpha$=0.2dB/km, $A_{eff}$=72$\mu$m$^2$, $n_2$=2.7x10$^{-20}$) or single mode fiber (SMF, D=17ps/nm/km, S=0.057ps/nm$^2$/km,$\alpha$=0.2dB/km, $A_{eff}$=80$\mu$m$^2$, $n_2$=2.5x10$^{-20}$). The loop can in turn be dispersion managed (DM) or unmanaged (noDM). In the first case, we use a single-periodic map with non-zero residual dispersion per span and the pre-compensating fiber is selected using the "straight line rule" [13]. In the second case, no dispersion compensation is performed along the loop and the pre-compensating dispersion is omitted. The propagation is modeled solving the coupled nonlinear Schroedinger equation (CNLSE) through the split step Fourier method (SSFM). To account for birefringence and PMD, each span is modeled as a concatenation of 50 random waveplates. The number of recirculations can be 1, 3 or 5, totaling 400, 1200 or 2000km. In all cases the propagation is noiseless and the equivalent noise of the link is loaded at the receiver (equivalent amplifier). We are thus ignoring the effects of nonlinear phase noise, which has been shown to

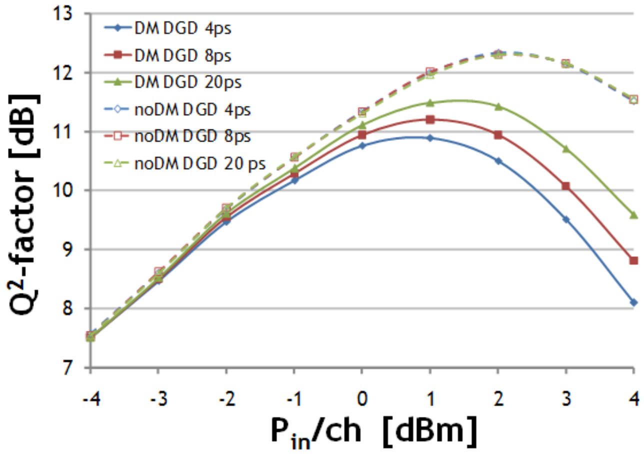


Figure 2: Basic simulative setup used in the simulationsBell curve for a 1200km link using NZ-DSF. Red circles: selected Pin for the six reported configurations.

be almost negligible in this kind of systems [14]. Before the receiver, we perfectly compensate for linear effects, i.e. chromatic dispersion and PMD, by inverting the Jones matrix of the simulated channel. This step replaces electronic compensation in the coherent receiver. This choice allows us to concentrate exclusively on the penalty arising from linear/nonlinear interactions along the link, neglecting any effect related to the non-ideal nature of DSP based compensation. At the receiver, the central channel is selected using a $2^{nd}$ order superGaussian optical filter with 56GHz bandwidth, then the signal beats with the local oscillator, is detected by ideal photodiodes at the output of a dual-polarization 90° hybrid and is ideally sampled at twice the baudrate. We neglect the phase noise of the local oscillator and we assume perfect frequency alignment between the signal and the local oscillator. The phase is estimated using a standard Viterbi&Viterbi algorithm with 9 taps to compensate for the cross phase modulation-generated nonlinear phase noise that arises during propagation [15]. We form a Monte Carlo estimate of the bit error rate (BER) by stopping the simulation when 100 errors are counted. Then the estimated BER is converted to $Q^2$-factor. For each combination of fiber type, dispersion map and distance, we test three different values of average DGD: 4ps, corresponding to a link with moderate PMD; an intermediate 8ps case; and 20ps, which, especially for shorter links, is a very large amount of DGD. In total we thus consider 36 possible combinations of length/fiber/dispersion map/DGD.

# 3 Numerical Results

We first need to assess the true impact of PMD/NL interactions, and need, for every configuration, a value of the average power per channel ($P_{in}$) that produces significant nonlinear effects. We will then estimate the $Q^2$-factor PDF at that value of injected power.

To this aim, we simulate the so-called "bell curves" for all the 36 possible combinations. These curves give the measured $Q^2$-factor versus $P_{in}$, at a fixed noise figure (NF) of the equivalent amplifier at the end of the link. Hence, increasing the injected power also improves the received optical signal to noise ratio (OSNR). In all the curves, there is a maximum $Q^2$-factor at a value of Pin which is commonly referred to as the nonlinear threshold (NLT). The length of the transmitted random pattern is 1024 symbols and for each value of $P_{in}$ we average the BER over 15 possible ISOP/fiber realizations in order to account for the variability induced by the PMD. Fig. 2 shows the bell curves for the case of a 1200km link using NZ-DSF. When using dispersion management, we see

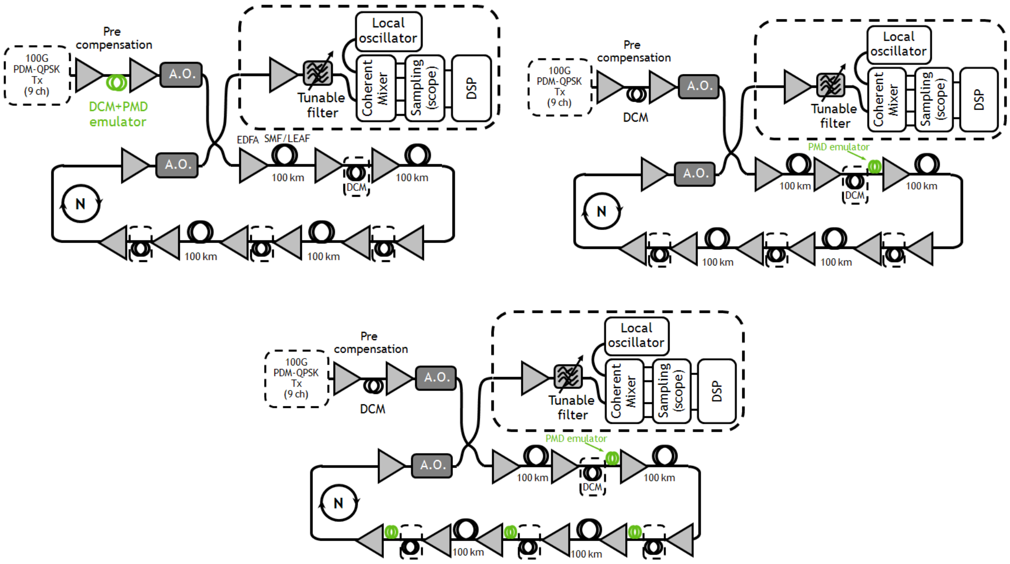


Figure 3: PMD emulator at the transmitter (top,left), one emulator trunk at each loop roundtrip (top, right) and one emulator trunk at each span (bottom).

that the total DGD has a positive impact on performance, since the DGD-induced depolarization reduces the impact of XPolM [14]. The measured $Q^2$-factor for the noDM case is instead almost independent of the DGD. These results, valid for all tested combinations of distance/transmission fiber, are consistent with the results in [14]. Once these bell-curves are available, we choose for all the 36 combinations the value of $P_{in}$ to be used when estimating the $Q^2$-factor PDF. We select the Pin that yields a $Q^2$-factor penalty (w.r.t the $Q^2$-factor at the NLT) of around 0.5-1dB in order to operate in the nonlinear regime, but close to realistic values of $P_{in}$. Also, given the selected power, we adjust the NF of the equivalent amplifier at the receiver in order to work at $Q^2$-factors around 10-11dB; this is done to both work at practical $Q^2$-factor and to limit the computational time required by the simulations.

We compare three PMD emulation schemes which could be easily used in a laboratory: (Tx case) Place a multi-section PMD emulator at the transmitter. In this case the emulator could be accommodated within a dual stage booster along with the pre-compensating fibers, as in Fig. 3 (top, left). (Loop case) Place a multi-section emulator in the loop, such that the signal crosses it at each roundtrip. In this case the emulator could be placed either in a dual stage amplifier together with the compensating fiber (as in Fig. 3 (top, right)) or, when no DM is used, in a dedicated dual stage with the power equalizer used to compensate for the amplifier gain profile. (Span case) Place a multi-section emulator in the dual stage amplifier at each span, along with the compensating fibers (Fig. 3 bottom).

These three schemes have an increasing complexity, but they also provide an increasing precision in catching the distributed effect of PMD/NL interaction. We want to derive some simple rules to understand when a certain complexity is "enough" for the system we want to study. We thus compare for each of the 36 considered configurations, the three proposed emulation schemes against the true case of distributed inline PMD. Each multi-stage PMD emulator consists of 10 randomly oriented waveplates. We simulate 500 random realizations of the PMD emulator settings at each evaluation of the $Q^2$-factor in order to estimate its PDF. For these tests we use a shorter pattern (256 symbols) in order to speed up the simulations.

Given the vast amount of tested cases, it would be impractical to present all the obtained PDF

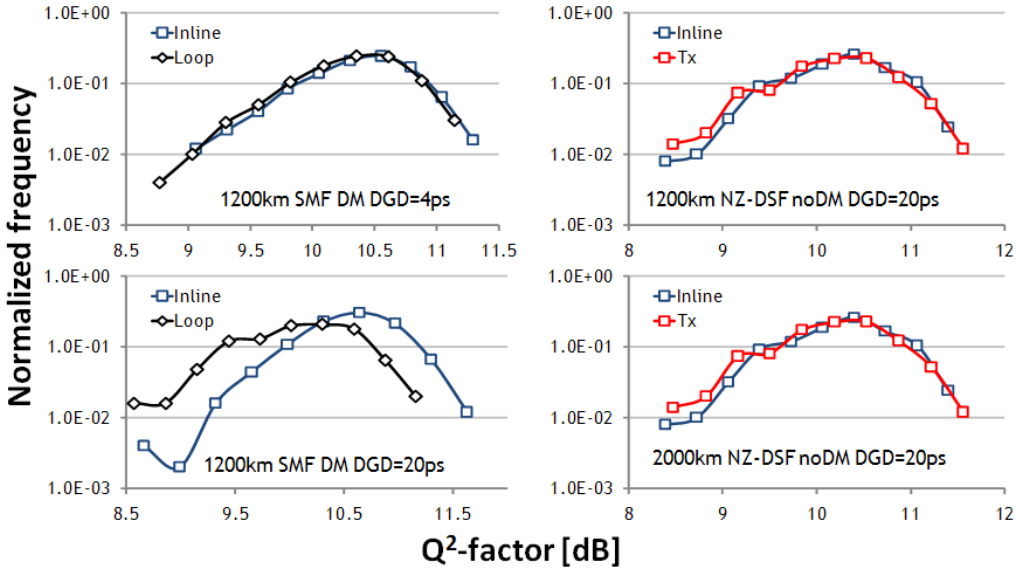


Figure 4: (top, left) 1200km link, SMF, DM, DGD=4ps, (bottom, left) 1200km link, NZ-DSF, noDM, DGD=20ps, (top, right) 1200km link, SMF, DM, DGD=20ps, 2000km link, (bottom, right) NZ-DSF, noDM, DGD=20ps.

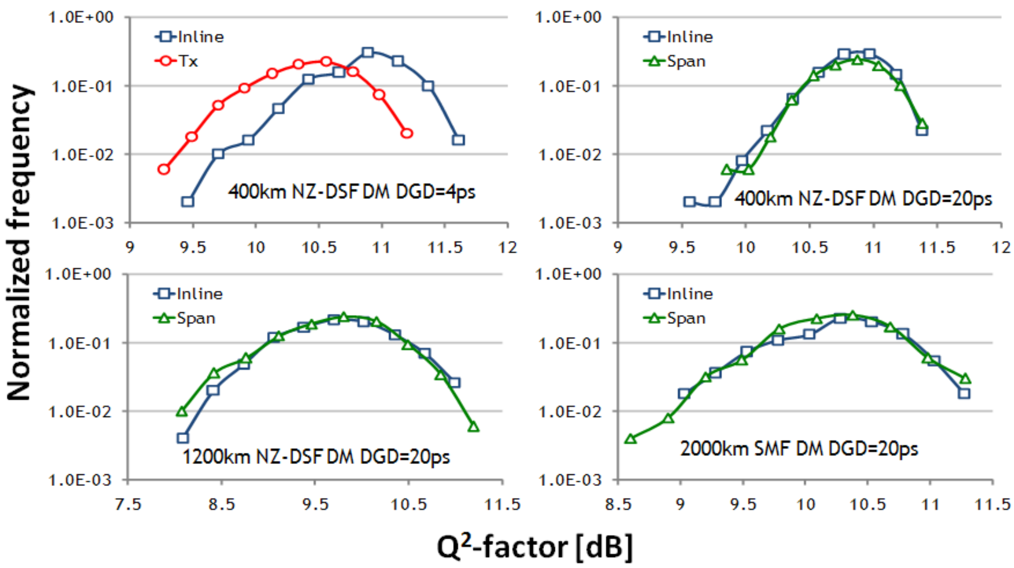


Figure 5: (top, left) 400km link, NZ-DSF, DM, DGD=4ps, (bottom, left) 400km link, NZ-DSF, DM, DGD=20ps, (top, right) 1200km link, NZ-DSF, DM, DGD=20ps, (bottom, right) 2000km link, SMF, DM, DGD=20ps.

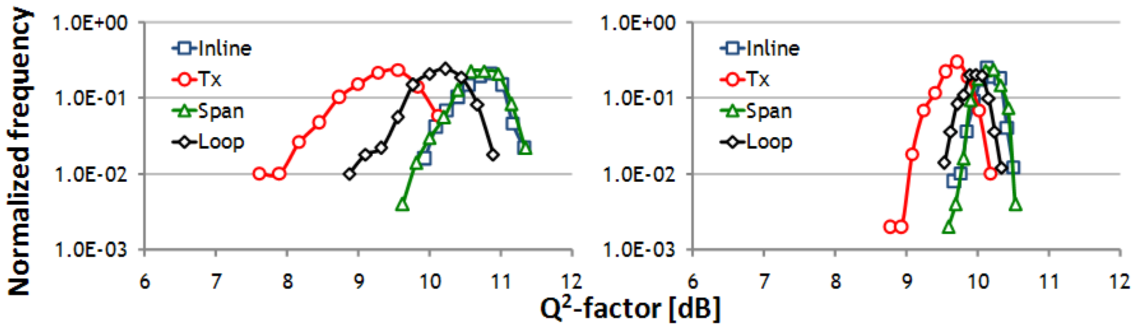


Figure 6: $Q^2$-factor PDF for 1200km DM NZ-DSF link with DGD=20ps, with (left) $P_{in}$=NLT and (right) $P_{in}$=NLT-2dB.

curves. We will summarize the most meaningful PDF trends with some examples provided in Figs. 4 and 5: (a) The larger the number of spans and/or the PMD of the link are, the larger is the number of emulator sections needed to reproduce PMD in the system. Looking at Fig. 4 (left) it is clear that using one emulator section per loop is enough for a 1200km link of SMF fiber with DM and 4ps of DGD, but not for the same system with 20ps of DGD. This is quite intuitive since the PMD is spatially distributed and thus when it gets very large, it is necessary to increase the number of emulators in order to correctly account for its effects. (b) PMD emulation at the transmitter is always accurate for dispersion unmanaged systems (Fig. 4 (right)). This is because here GVD largely dominates over PMD and thus a very simple emulation scheme is sufficient to provide accurate results. (c) When considering dispersion managed systems, PMD emulation at the transmitter is always inaccurate in all the considered tests, even on short links with a small amount of PMD (Fig. 5 top, left). We conclude that when DM is present, PMD/NL has a clear impact and an accurate emulation scheme is required. (d) With DM, independently of the transmission fiber, also using one emulator at each loop round trip can lead to inaccurate PMD estimation for large values of DGD even for 1200km links (Fig. 4 bottom, left). (e) The only emulation scheme that proved to be accurate and reliable in all the 36 tested configurations is the one using a PMD emulator at each span. If an increased complexity of the PMD emulation setup is acceptable, it guarantees precise estimation of the effect of PMD in a variety of link configurations (Fig. 5).

To complete the analysis we test the impact of two more parameters. First we verify that our conclusions hold also at lower values of Pin. In fact, we tested our system using a Pin larger than the NLT to enhance the PMD/NL interactions, but it is interesting to confirm that our results are also valid at the NLT or even at lower powers. Fig. 6 shows results for a 1200km, NZ-DSF system with DM and DGD=20ps, for two different input powers. On the left $P_{in}$=NLT, while on the right $P_{in}$=NLT-2dB. In both cases the conclusion that neither an emulator at the Tx, nor one per loop are enough to emulate the NL/PMD interactions (cfr. Fig. 4 bottom left) holds at the NLT and is still valid at lower powers. Another test is to consider the impact of the number of waveplates at each emulator on the PDF. We decided to use 10 waveplates per emulator in our simulations in order to reproduce higher order PMD. However it would be very interesting to use just one PMF, i.e. one waveplate with a given DGD, to reduce the hardware. Fig. 7 shows results with a variable number of waveplates ($N_w$=1, 2, 5, 10) for a 2000km DM link on SMF fiber, with DGD=20ps, and one emulator at each span (left) and with DGD=4ps, and one emulator at each loop (right). In both cases using a single waveplate is equivalent to the use of an emulator with 10 waveplates. We thus understand that the PMD/NL interaction in each fiber span is dominated by $1^{st}$ order PMD.

As a final remark, it is important to note that in our analysis we didn't consider the effect of

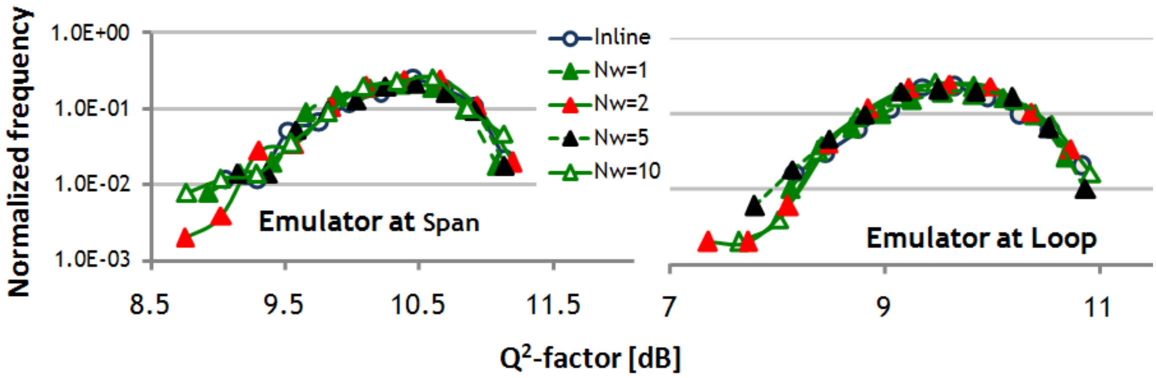


Figure 7: Impact of the number of waveplates per emulator for a 2000km DM link on SMF fiber with: DGD=20ps, one emulator per span (left): DGD=4ps, one emulator per loop (right).

polarization dependent loss (PDL). The interaction of PDL, PMD and nonlinear effects is still an open topic in research [16], but in general the main effect of PDL is to induce a stochastic variation of the received OSNR [16, 17]. In our study this would translate into an increased variance of the measured Q-factor. However this increase should weakly depend on the amount of PMD or on the PMD-emulation technique employed. Moreover it has recently been show [18] that polarization multiplexed systems are less affected by PDL than single polarization systems.

# 4 Conclusions

We analyzed different solutions to emulate PMD/NL interaction in 100Gb/s PDM-QPSK systems using numerical simulations. The optimal emulation scheme depends on many factors such as transmission fiber, dispersion map, total distance, and DGD, and should be carefully selected to avoid wrong performance estimation. As a general rule, when using dispersion management, a PMD emulator should be placed at least at each loop roundtrip. For large values of DGD (20ps, in this work) this is insufficient and an emulator should be placed at every span. With noDM, the effect of PMD is minor due to the extremely large cumulated dispersion. Placing the emulator at the transmitter assures correct emulation of the PMD in all the tested cases. The same conclusions still apply when using input powers around the NLT. The number of waveplates per emulator can be reduced to 1 (PMF fiber), since the PMD/NL is dominated by 1$^{st}$ order PMD.

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