Abstract

Improving the tolerance to polarization mode dispersion (PMD) is considered to be one of the major prerequisites for the success of modern high bit rate optical communication systems. Various approaches such as optical compensation, electrical mitigation, multi-level modulation formats promise to increase the PMD tolerance of optical systems, whereas the question of how to experimentally characterize these solutions needs to be answered before commercial deployment. This is not an easy task since these systems need to be characterized with respect to first and higher order PMD but also with respect to their dynamic behavior. We show that deterministic polarization controllers combined with in-situ measurement of PMD can help to explore the PMD tolerance of an optical communication system and to generate reliable and repeatable results by avoiding statistical elements such as polarization scramblers. These elements can be combined to form a PMD testbed which allows to stress a system by applying a deterministic amount of PMD including a well-defined rate of change. Such a PMD testbed can be used during development of adaptive mitigators as well as for compliance testing. Finding an agreement on standard test procedures for such a testbed will make the evaluation of PMD tolerant receivers easier and more comparable.

Keywords: PMD, PMD Measurement, PMD Tolerance, PMD Testbed, Polarization Synthesizer, In-situ PMD

1. Introduction

The main objective of determining the PMD tolerance of an optical transmission system is to find out on which fiber link it can be operated with the desired availability. Although the aim seems very obvious, it turns out to be a rather complicated task to guarantee a predefined outage probability for a transmission system on a specific fiber link. Main reason for that is the statistical nature of PMD which always leaves a risk that the fiber link moves to a state exceeding the PMD tolerance of the system.

The established way of tackling this problem is to determine the tolerance of the system with respect to differential group delay, DGD. A typical value for the DGD tolerance of a system would be approximately 30% of the bit period, i.e. 8 ps for a 40 Gbit/s system. Considering that the instantaneous DGD of a fiber link can be approximately 3 times higher than the PMD value (due to the Maxwellian distribution of the DGD), the maximum tolerable PMD would be 2.7 ps. Although being very simple, this rule-of-thumb leads to design rules which can easily be applied in the field. However, this practical rule works because the estimated tolerance is rather conservative. At a bit rate of 10 Gbit/s, this might be acceptable, but a maximum tolerable PMD of 2.7 ps will disqualify most long haul fiber links for the use of 40 Gbit/s data rate. Therefore, network operators consider a PMD tolerance of around 8 ps to be desirable. This would allow a sufficient number of links to be upgraded to 40 Gbit/s.

To achieve this tolerance at these data rates adaptive systems will apparently be part of the receiver to improve the quality of the received signal. These systems can be optical systems (e.g. optical PMD compensators) but also electronic systems (e.g. Viterbi decoders). In any case, an adaptive system will add dynamic properties to the receiver and thus raises the need for characterizing the dynamic performance.

Characterizing the dynamic performance of a PMD tolerant receiver means to examine the ability of the receiver to follow different sorts of perturbations, i.e. stress patterns. Choosing certain stress patterns is closely linked to the question about the required speed of a PMD compensator. Published results show that PMD fluctuations can be in the order of sub-milliseconds [1, 2]. However, most of the time, the PMD varies much slower and tends to have time constants of minutes to hours [3, 4]. It is obvious that an aerial fiber is likely to exhibit a different fluctuation pattern than a buried fiber. Therefore, a method for characterizing dynamic properties of a receiver which does not act on assumptions about the fiber link would be helpful. This will lead to an objective characterization comparable to the frequency-response of an amplifier. Having gathered information on the dynamic receiver properties, the individual dynamic properties of a fiber link can be compared and a qualified decision can be made whether the receiver can be used on this particular link or not.
In the following paragraphs, we propose a PMD testbed which allows to characterize an optical receiver statically and dynamically with respect to its PMD tolerance.

2. PMD Test Requirements

Several aspects need to be considered to fully assess the PMD tolerance of an adaptive receiver:

- **Static Characterization**
  In a first step, the static behavior of the receiver needs to be examined. This can be done by inserting a controlled amount of PMD into the system and observe the BER degradation. The most effective way is to use PMD emulators with an adjustable amount of first and second order PMD.

- **Dynamic Characterization**
  Fast polarization controllers (e.g. electro-optic devices) can be used to apply well-defined dynamic changes to the system. We propose to use polarization controllers in combination with a polarimeter (SOP Synthesizers) to introduce deterministic perturbations (see Fig. 1).

*Repeatability/Deterministic Adjustment*

Current test solutions use random polarization scramblers to either remove dependence on input polarization or to examine dynamic behavior. Since the movement rate of these scramblers changes according to a statistical distribution, it is important to measure over a sufficiently long time. This drawback can be overcome by using SOP synthesizers which allow to deterministically reproduce states of the emulator and to exactly repeat the same measurement at a different time. This is a crucial point if measurement results of different receivers are being compared.

*Verifying the Emulator PMD*

In order to verify the settings of a PMD emulator, it would be useful to measure the current PMD state of the overall system including the input polarization state (State of Polarization, SOP). In addition, this information could be used to adaptively move to a predefined state which increases the repeatability of the system. We propose to use a spectral resolving polarimeter (Polarization Spectrometer) to analyze the received data signal. The spectrally resolved polarization state allows to derive information on the PMD-induced distortion. [5,6]

![Figure 1. A polarization synthesizer (SOP Synthesizer) comprises a polarization controller and a polarimeter. In feedback operation, predefined polarization states can be precisely reproduced and temperature variations are effectively compensated.](image-url)
3. PMD Emulation

Common ways of generating PMD are shown in Fig. 2. Pure first order PMD can be generated by the setup shown in Fig. 2(a). Such a component has two frequency-independent principal states of polarization (PSP), the fast PSP and the slow PSP. The signal is divided into two orthogonally polarized components. Typically, the delay of one component can be adjusted by a motor-driven moveable mirror. The DGD of this emulator can be very accurately controlled. For system tests, a polarization scrambler is added at the input to remove the dependence on input polarization. However, using a scrambler introduces statistical behavior to the system which increases measurement time. Furthermore, this setup is unable to generate higher order PMD.

Fig. 2(b) shows a common approach to generate higher order PMD [7]. The emulator consists of a number of birefringent elements which are connected by polarization controllers. Typically, the polarization controllers are controlled in a random way. If the number of DGD elements is sufficiently high (e.g. 15, [7]), the Maxwellian DGD statistics of a real fiber can be reproduced. The main disadvantage is that, as in reality, the interesting cases with high instantaneous DGD are very rare since they correspond to the tail of the Maxwellian distribution. Furthermore, the speed of change is usually not well controllable.

Fig. 2(c) shows an emulator based on rotatable birefringent crystals. Since the differential phase delays are very stable, these kinds of setups allow deterministic adjustment. However, mechanical movement of the crystals limits the maximum tuning speed.

All these setups are not designed to deterministically reproduce certain PMD settings. This problem can be solved by using SOP synthesizers instead of random scramblers (see Fig. 1). SOP synthesizers control the SOP in a feedback loop and are capable of compensating inaccuracies caused by temperature drift.

Note that the DGD elements in Fig. 1b are often implemented by polarization maintaining fiber (PMF). This will prevent deterministic control because of the strong temperature dependence of the PMFs and the unknown differential phase delay of the fast and slow axis. In principle the differential phase delay can be compensated by the SOP synthesizers. However, the appropriate settings cannot be predicted and have to be measured. To achieve fully deterministic operation, the instantaneous overall PMD can be measured using a polarization spectrometer. This provides a feedback signal allowing to precisely reproduce the emulator state and the input polarization state.

Fig. 2: (a) Adjustable DGD with SOP scrambler at input. (b) Emulating fiber statistics by means of cascaded DGD sections and scramblers. (c) Deterministic creation of higher order PMD by rotating birefringent crystals.
4. IN-SITU PMD MEASUREMENT

The Jones Matrix Eigenanalysis (JME) is an established way for characterizing the PMD of an optical system [8]. The JME measures the frequency-dependent Jones matrices by stimulating the system with a tunable laser source and monitoring the output SOP as a function of input SOP and optical frequency. To assess the state of a PMD emulator, the principle implies that data transmission and PMD measurement cannot be done in parallel, i.e. the data signal has to be turned off and the tunable laser source has to be connected to the input of the PMD emulator. As opposed to this approach, in-situ PMD measurement methods use the received data signal to assess data on the link/emulator PMD. They can be divided into intrusive and not-intrusive methods.

4.1 Non-Intrusive In-Situ PMD Measurement

Non-intrusive PMD measurement methods are particularly interesting for monitoring the PMD in a transmission system. Since no manipulation on the transmitter side is necessary, these methods can easily be used in field applications [5, 6]. Fig. 3 shows an experimental setup. For the non-intrusive method, the polarization controller at the fiber input is not needed. The evaluation of the measurement data is closely linked to the Poincaré Arc Method [9, 10]. Usually, a swept laser source is used at the input of the fiber sweeping the operating wavelength while a polarimeter observes the output SOP trajectory. Here, the received signal is analyzed by a scanning optical band pass filter. In this way, the modulated broadband signal is used as stimulus and the SOP of the filtered signal can be used to derive an SOP trajectory which can be evaluated similarly to the SOP trajectory of the Poincaré Arc Method.

For a given input SOP, the output SOP changes according to

\[
\frac{d\delta}{d\omega} = \hat{\Omega} \times \hat{s} \quad \frac{d\delta}{d\omega} = 2\sqrt{\gamma (1-\gamma)} \cdot DGD
\]

(1)

The input SOP is expressed by means of the power splitting ratio \( \gamma \). The output SOP rotates around an axis determined by the output PSPs. Thus, the trajectory is a part of a circle the diameter of which depends on the power splitting ratio (Fig. 4).

The angular rotation rate of the SOP depends on the fiber DGD [11]:

\[
DGD = \frac{d\phi}{d\omega} \quad (2)
\]

Fig. 4: For pure DGD, the frequency resolved SOP trajectories are circles on the Poincaré sphere. The diameter is dependent on the power splitting factor \( \gamma \), but not the angular variation as a function of frequency.

During a measurement cycle, the band pass filter is swept across the signal spectrum and the corresponding SOP trajectory is recorded. Let \( \hat{s}(\omega) \) be the Stokes vectors of the recorded SOPs. For low enough second order PMD, the PSPs can be found using three SOPs of the measured trajectory with maximum distance:

\[
\Delta s_q = \hat{s}_q - \hat{s}_p \quad \Delta s_r = \hat{s}_r - \hat{s}_q \quad p < q < r
\]

\[
PSP = \frac{\Delta s_q \times \Delta s_r}{|\Delta s_q \times \Delta s_r|} \quad (3)
\]

Fig. 3: In-Situ PMD Measurement. The received data signal is analyzed by means of a scanning band pass filter and a polarimeter. In this way, the spectral dependence of the output SOP is measured allowing to analyze PMD-induced distortion.
The power splitting ratio can be calculated using the following relationship:

\[ \gamma = \frac{1}{2} \pm \frac{1}{2} \sqrt{1 - \frac{\Omega^2}{\Omega_0^2}} \]  

(4)

Now that \( \gamma \) and \( |d\mathbf{s}/d\omega| \) are known, the DGD can be calculated using eqn. (1). Measuring the DGD in this way only works if \( \gamma \) is not close to zero or one. Simulations show that if \( \gamma \) is close to zero or one, measurement accuracy is reduced dramatically due to the limited accuracy of the polarimeter. However, this drawback can be accepted since these are cases where the signal is traveling in one of the principal states and is not disturbed by the fiber PMD. In other words, the accuracy of the PMD measurement only fades for cases where the signal is not disturbed by PMD, anyway.

### 4.2 Intrusive In-Situ PMD Measurement

If it is allowed to change the input polarization, the setup of Fig. 3 can be used to perform a JME-like evaluation. The input polarization controller can generate three or more predefined states. The polarization spectrometer at the output is measuring the SOP trajectories corresponding to each input polarization state. The collected data is equivalent to the measurement data which would be collected with the traditional JME. Thus, the evaluation yields the frequency resolved Jones matrices as well as first and second order PMD. During the measurement, the transmission system may continue transmitting data, however due to the change of input polarization, BER fluctuations may appear during the measurement.

Fig. 5 shows experimental results which have been measured in the labs of Lucent Technology in Nuremberg as part of the government funded project “Efficient Integrated Backbone” (EIBONE). The signal of a 40 Gbit/s transmitter was passed through a higher order PMD emulator and measured using the intrusive in-situ PMD measurement approach. The tunable band pass filter was realized by a scanning Fabry Perot filter with a bandwidth of 1.7 GHz and a free spectral range of 170 GHz. The scanning period was 100 Hz. It could be shown that the results are matching the results of the traditional JME fairly well (see Fig. 5).

![Graph showing experimental comparison between intrusive PMD measurement and JME. The in-situ results are generated using a 40 Gbit/s signal and a scanning Fabry Perot filter with 1.7 GHz bandwidth.](image-url)
5. Dynamic PMD Emulation

Combining the aforementioned techniques of emulating and measuring PMD allows deterministic operation of a PMD testbed. Furthermore, they offer a way to deterministically change the PMD at well defined movement rates. This is a clear improvement compared to established scrambling schemes. However, questions regarding appropriate stress patterns and the appropriate movement rates arise. A first suggestion is given in Fig. 6. This setup is restricted to pure first order PMD. The SOP synthesizer at the input of the DGD element is capable of changing the $\gamma$ factor. The SOP synthesizer at the output of the DGD element can move the output SOP. The polarization spectrometer monitors the PMD-induced signal distortion and allows to adaptively find the appropriate settings of the polarization controllers during the training phases (see below).

5.1 $\gamma$-Variation

Among all the possible variations which could be introduced by the first SOP synthesizer, we propose to move the input SOP in a way that the $\gamma$ factor oscillates between 0 and 1. This leads to a well defined SOP trajectory at the input of the DGD element and can be considered as worst-case situation for input polarization changes since the distortion will vary between the extreme values. To generate this oscillation, the input SOP has to be moved on a great circle on the Poincaré sphere. If this circle intersects the two input PSPs, the $\gamma$ factor will oscillate between 0 and 1. The second SOP synthesizer is not changed during this test.

5.2 Training Phase for $\gamma$-Variation

To generate the appropriate circular input trajectory, it is necessary to know the orientation of the PSPs in Stokes space. Measuring the orientation of the PSPs can be done in a training phase. One way of finding the PSPs is to set the DGD element to a high value and to minimize signal distortion by adjusting the input SOP and observing the readout of the polarization spectrometer. If the distortion vanishes, the input SOP is aligned to the input PSP. The second PSP will be on the opposite side of the Poincaré sphere. Once knowing where the PSPs are located on the Poincaré sphere, the SOP synthesizer at the input can be programmed to move on a circular trajectory intersecting with this PSPs.

5.3 PSP-Variation

Considering an optical PMD compensator which tracks the PSPs of the transmission system, the worst-case situation would be to move the emulator PSPs on a great circle on the Poincaré sphere. To keep the overall system in a compensated state, a PMD compensator will create a certain amount of DGD and aligns the compensator PSPs in a way that the fast compensator PSP matches the slow PSP of the emulator and vice versa. Thus, continuously moving the emulator PSPs on a great circle will create the maximum angular PSP variation. The maximum stress for a compensator is generated if the $\gamma$ factor is set to 0.5. In that case, both PSPs are equally excited. However, different compensator concepts may exhibit problems particularly for $\gamma$ values unequal to 0, 1 and 0.5. The PMD testbed allows to explore this behavior in a deterministic way. Furthermore, the ability of the compensator to endlessly track the PSP changes can be verified.
5.4 Training Phase for PSP-Variation

Finding the appropriate settings for the second SOP synthesizer is more difficult than for the \( \gamma \) variation. The goal is to move the output PSP on a great circle. Considering that \( \gamma \) is set to 0.5, that does not necessarily mean that the output SOP is moving on a great circle as well. The solution is to adaptively find the appropriate settings of the second SOP synthesizer during a training phase. The appropriate voltage sequence is reproduced during the measurement phase without feedback operation. Finding the appropriate voltage sequence during the training phase can be done by aligning the input SOP to the PSP like it is done for the \( \gamma \)-variation. Having one PSP excited, the current SOP is identical with the output PSP. Thus, the second SOP synthesizer can be programmed to let the SOP move on a great circle. Repeating the voltage sequence will let the PSP continuously move on a great circle even when the input SOP is changed.

5.5 Variation Speed

As mentioned before, the necessary tracking speed of a PMD tolerant receiver may depend on the particular link. It would therefore be helpful to characterize the tracking speed without making assumptions on the fiber link. This would make measurement results of different receivers comparable.

The free parameter in the aforementioned test methods is the rotating speed of the SOP or PSP. We propose to successively increase this rotation speed until the compensator or receiver fails to follow. Using LiNbO\(_3\), technology inside the SOP synthesizers can provide maximum tuning speeds in the order of microseconds. This allows fast enough stimulation to characterize the frequency response of the involved control loops.

5.6 Different Compensator Approaches

In order to create a defined amount of stress for a PMD tolerant receiver, both aforementioned tests are important. An optical PMD compensator is likely to be less vulnerable against \( \gamma \) changes since once being aligned to the PSPs, changes of \( \gamma \) will not severely affect signal quality since the cumulated PMD (emulator and compensator) vanishes. Whereas a compensator operating in the electrical domain, i.e. after the photodetector, will not be vulnerable to PSP changes since polarization changes of the second SOP synthesizer are not visible for the polarization-independent photodetector.

5.7 DGD Variations

Direct changes of DGD are difficult to generate using the setup in Fig. 6 since motorized DGD elements cannot generate fast DGD changes. Besides that, the moving mirror concept creates very quick SOP rotation at the output during the adjustment process (approximately 2000 revolutions per 10 ps DGD change).

Although not being exactly the same as a change of DGD, the \( \gamma \) factor can be used to create similar effects. Starting from \( \gamma = 0 \) and a DGD unequal to zero, the signal is not distorted because of the PSP alignment. An adaptive receiver or compensator cannot distinguish between this case and a case where the emulator DGD is zero. The compensator will probably move to a neutral state. Now changing \( \gamma \) to a nonzero value, e.g. 0.5, will force the adaptation algorithm to adjust to the upcoming amount of DGD. This is similar to an instantaneous increase of DGD and can be used to explore the ability of a compensator to react to instantaneous DGD changes.

6. Conclusion

We consider a standard way of characterizing optical interfaces with respect to PMD tolerance to be crucial for the success of adaptive receiver concepts. An agreed standard would make different implementations or even different concepts (e.g. electrical, optical compensation) more comparable. Network operators will only accept the additional complexity if it can be proven that the new concepts do not add additional risk of failure to the system.

These proofs can only be brought by more refined test and measurement methods as it is suggested in this article. As opposed to field tests, these concepts allow to create repeatable stress situations which may only rarely occur in reality.

The setup discussed in this article focuses on pure first-order PMD. Although the DGD element can easily be replaced by a higher-order PMD emulator, this will increase the degrees of freedom dramatically. In order to keep the testing time as short as possible, further investigations will be necessary to define appropriate tests for higher order PMD emulation.

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References


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