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Random Birefringence and its Impact on Optical Fiber Communications

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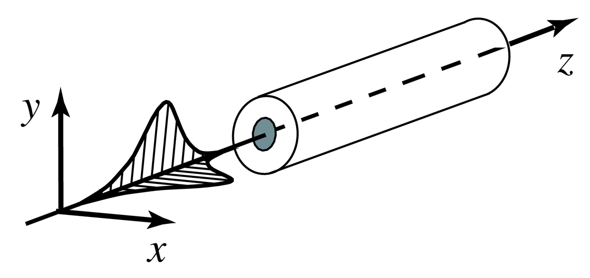
1. Intro

1.1. Optical Fiber Communications Systems

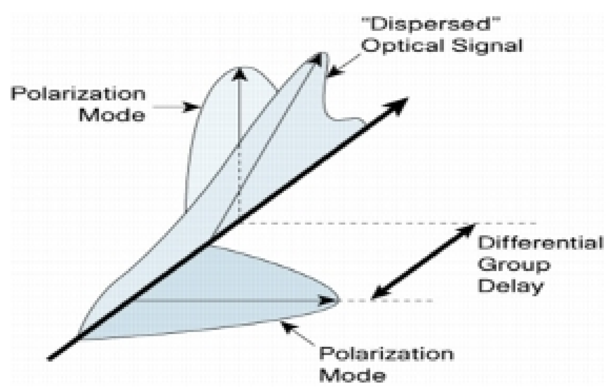
Optical fibers are the standard medium for telecommunication and data transmission, thanks to their enormous bandwidth capacities. Data in a fiber is sent as binary light pulses, composed of two orthogonal polarization components which are then recombined by the receiver at the destination.



1.2 Birefringence

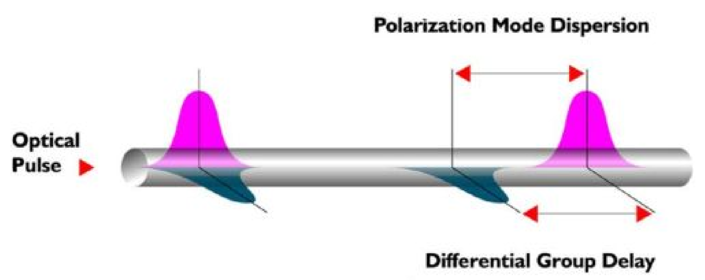
Ideally, each fiber's core has a perfectly circular cross-section, which makes the signal polarization irrelevant because both components of the signal propagate in an identical way.

In real fibers, however, the circular symmetry is broken. The asymmetries, which are caused by random imperfections in manufacturing and by the stresses of installation, cause the two polarization components of the signal to propagate with different speeds through the fiber. The two components of the signal will therefore separate, causing the data pulses to spread. This phenomenon is called birefringence, and the spread between the two components of the signal is known as the Differential Group Delay (DGD). DGD is normally measured in picoseconds (1ps=10^{-12} seconds).



1.3 Polarization Mode Dispersion (PMD)

The axes of birefringence and the strength of the birefringence vary randomly with distance, time, temperature and wavelength, giving rise to random distortions of the optical signals. This phenomenon is called Polarization Mode Dispersion (PMD), and limits the speed at which data can be successfully transferred over the fiber.



Acknowledgments

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URGE to Compute

2. Description of PMD

2.1 The PMD Vector

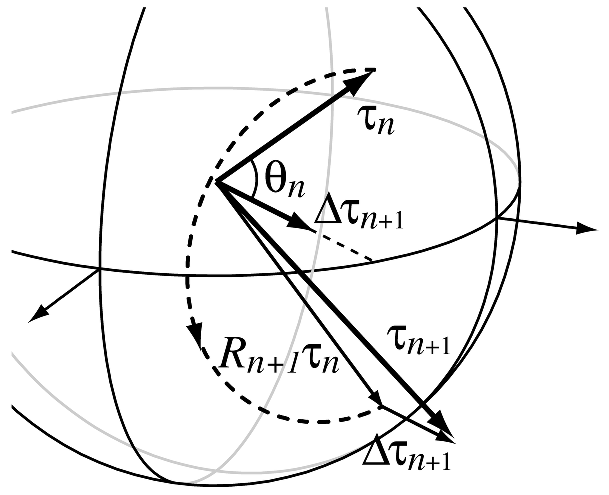
PMD can be quantified by a real 3-component vector, called the PMD vector $\tau(\omega, z)$, which is distance- and frequency-dependent. The PMD vector points in the direction of the slow axis of birefringence (slower polarization of the light), and its length is the DGD. Each birefringent fiber section has an associated PMD vector.

2.2 The PMD Concatenation Equation

When fiber sections are joined, the corresponding PMD vectors combine according to the PMD concatenation equation:

$$\tau = R_2\tau_1 + \tau_2$$

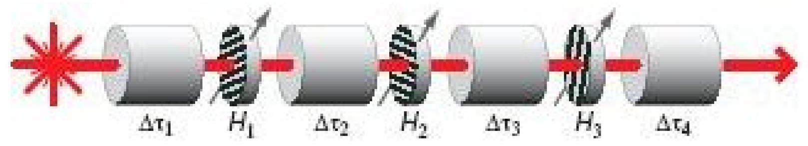
where R_2 is a 3x3 real rotation matrix that characterizes the 2nd section.



2.3 The Hinge Model

Traditional models of PMD assume that the PMD vector of each section is an independent random vector. Recent experiments, however, have shown that this model does not represent the behavior of installed systems. In its place, a "hinge" model was proposed. The hinge model characterizes a transmission link as composed of long sections of fiber whose properties are fixed in time; these sections however are separated by "hinges," which are subject to environmental effects that affect their PMD properties. By themselves, the DGD added by the hinges is negligible, but their presence affects the total PMD via the rotation matrices. The PMD concatenation equation in the hinge model is therefore

$$\tau_{n+1} = R_{n+1}H_n\tau_n + \Delta\tau_{n+1}$$



2.4 What are Hinges?

Hinges are short sections of fiber that act like rapidly varying polarization transformers. In practice, hinges are servicing huts, or fiber sections that are exposed to temperature variations and/or mechanical vibrations such as lines that run along railroad tracks or over bridges. In contrast, the PMD of long sections of fiber that are buried underground remain stable for weeks or even months.

2.5 Isotropic vs Anisotropic Hinge Models

Most mathematical studies of the hinge model assume that the hinge rotation matrices scatter the direction of the PMD vector uniformly across the sphere. We refer to this as the "isotropic" hinge model. While convenient, this is an unrealistic assumption. Consistent with recent experimental studies [5], an anisotropic hinge model was recently proposed [1] in which the hinges are assumed to produce a random rotation about a static axis.

3. System Impact of PMD

3.1 Power Margin and System Outages

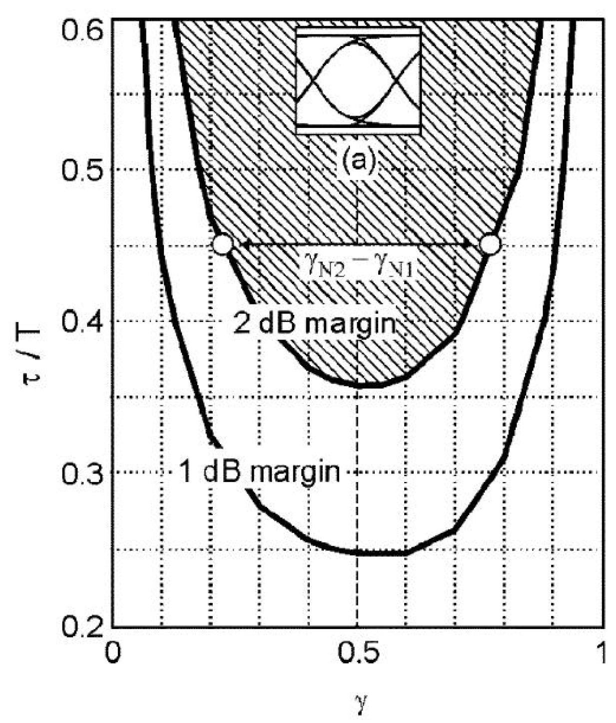
The power margin is the difference, in dB, between the optical signal-to-noise ratio (OSNR) at the receiver and the minimum OSNR required to insure that a specified bit-error ratio is not exceeded. The power margin is independent from PMD, and OSNR margins are allocated by the system designer. Any time PMD-induced distortions exceed the power margin, an outage occurs.

3.2 Outage Probability - Power Splitting Ratio

In general, system outages occur when the DGD is unusually large. The precise connection between PMD and system outages also depend on the relative orientation between the signal polarization and the total PMD vector. The power splitting ratio (γ) is the fraction of signal energy aligned with slow principal state of polarization, and as such it depends on both the state of polarization of the input signal and the total PMD vector of the transmission line.

3.3 Outage Map

The PMD-induced outage probability can be computed via the outage map approach. Outage maps are plots of constant OSNR margins as a function of the DGD and the power splitting ratio. The outage region comprises all combinations of DGD and power splitting ratio whose occurrence cannot be accommodated by the allocated PMD margin. Outage maps can be used to compute the outage probability of any wavelength band. The isotropic hinge model assumes γ to be uniformly distributed. In the anisotropic hinge model, this assumption is not justified.



The outage map defines the boundary of the outage region.

3.4 NCR

Outage probabilities are required to be extremely rare, on the order of minutes—or seconds—per year. The precise value, specified by the manufacturer, is called the outage specification, or P_{spec}. Any wavelength band whose calculated outage probability exceeds P_{spec} is then said to be non-compliant. The expected value of the fraction of the number of channels that have an outage probability greater than Pspec is called the Noncompliant Capacity Ratio (NCR).

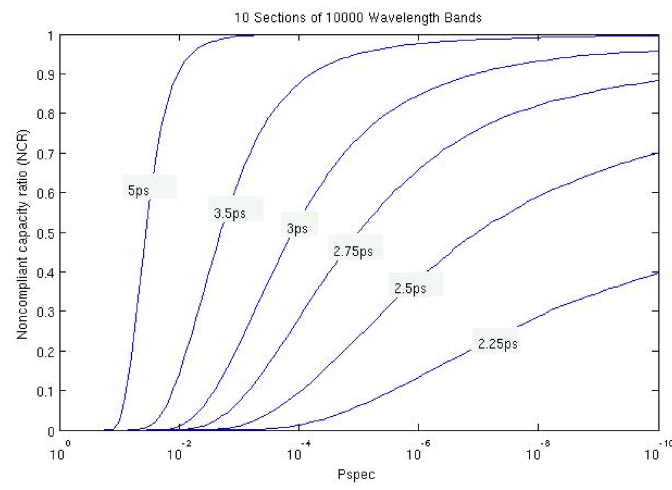
$$\text{NCR} = \text{E}[P_{out} > P_{spec}]$$

In the traditional model of PMD, all wavelength bands are statistically identical, and therefore they are all compliant or non-compliant: The NCR is either 0 or 1. In the hinge model, however, statistical differences exist among different wavelength bands, and therefore each band will experience a different outage probability. This results in only a certain fraction of the bands being noncompliant.

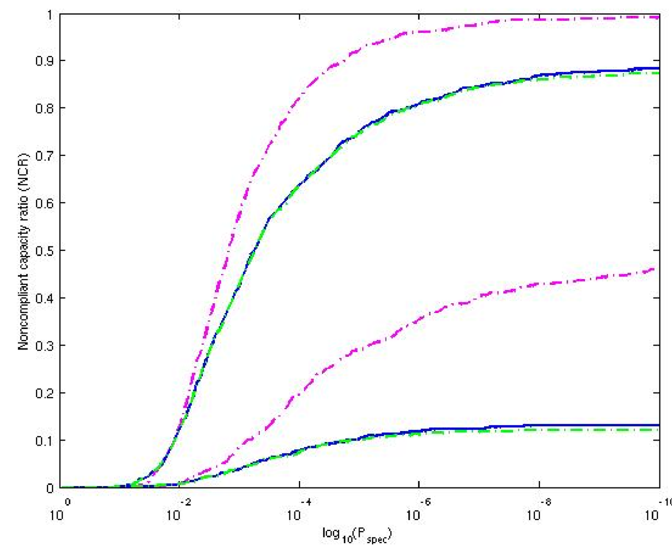
4. Simulations and Results

4.1 Numerical Simulations

We have studied and compared the outage statistics of four unique hinge models. In practice, the NCR was computed using the methods described in the accompanying poster.



item This graph is the NCR as a function of Pspec with 40Gb/s NRZ modulation for the isotropic hinge model. This plot is for links of 10 sections. Each link's mean DGD is indicated on each curve.



This graph is the NCR for the isotropic model as well as the anisotropic model for a uniform and non uniform splitting ratio. The purple dot dashed line is for the isotropic model, the solid blue line is the anisotropic uniform and the dashed green is the anisotropic non-uniform. The Top three lines are for ten sections with mean DGD of 3.0 ps and the bottom three are for six sections with mean DGD of 2.5 ps.

4.2 Results

Our results show that (i) the isotropic model overestimates the NCR compared to the anisotropic models, and (ii) there are also significant variations among different anisotropic models. These differences indicate that PMD-induced outages strongly depend upon the way in which the PMD is physically generated in the system. This indicates that our current models may not accurately describe PMD in installed systems, and that a more refined model may be required to quantitatively describe real-world PMD-induced outages.

References

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