Random Birefringence and its Impact on Optical Fiber Communications

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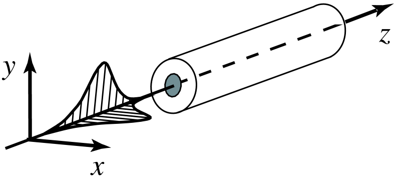
November 20, 2009

Outline

1. Basics of Optical Fiber Communications Systems
2. Polarization Mode Dispersion
3. Hinge Models
4. Results and Conclusions

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; the electric field contains two orthogonal polarization components.
- Ideally, each fiber's core has a perfectly circular cross-section, in which case both components of the signal propagate identically.



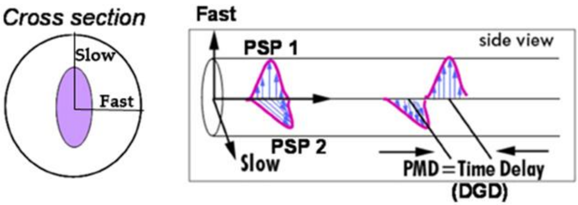
Birefringence

- Birefringence = double refraction

  It occurs when materials are deformed such that isotropy is lost (ie, due to manufacturing imperfections or when the fiber is stretched or bent).
- Birefringence causes the two polarization components of a signal to propagate with different speeds.
  In turn, this causes the two components of a light pulse to split.
- The axes of birefringence and the strength of the birefringence vary randomly with distance, time, temperature and wavelength.
- This phenomenon is called Polarization Mode Dispersion (PMD), and limits the speed at which data can be successfully transferred over the fiber.

Polarization Mode Dispersion

- The spread between the two components of the signal is known as the Differential Group Delay (DGD).
- PMD can be quantified by a real 3-component vector, $\vec{\tau}(\omega, z)$, which is distance- and frequency-dependent.
- The PMD vector points in the direction of the slow axis of birefringence, and its length is the DGD.
- Principal states of polarization = axes of birefringence of the fiber.

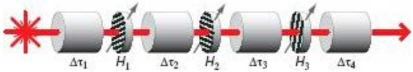


The Hinge Model

Two kinds of elements influence the total PMD of a system:

1. Long sections of fiber optic cables (10's to 100's of km)
   - Usually buried underground and insulated, so environment remains relatively stable for weeks at a time.
   - Properties can be considered to be fixed in time.
2. Hinges (1–100 meters)
   - Amplifiers, servicing huts, or fiber sections exposed to temperature variations and/or mechanical vibrations such as lines that run along railroad tracks or over bridges.
   - They connect long fiber sections.
   - Their birefringence varies rapidly.
   - They add negligible DGD by themselves, but they affect the total PMD via the rotation matrices.

Typical systems have a relatively small number of sections.



The PMD Concatenation Equation

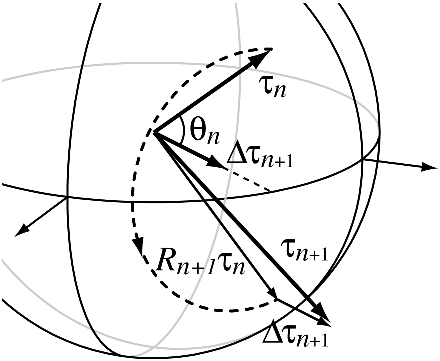
- When fiber sections are joined, the corresponding PMD vectors combine according to the general PMD concatenation equation:

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

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

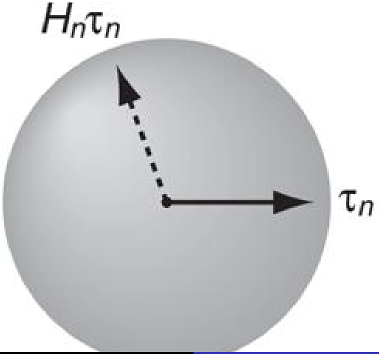
- The specific PMD concatenation equation that we use in the our model is

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



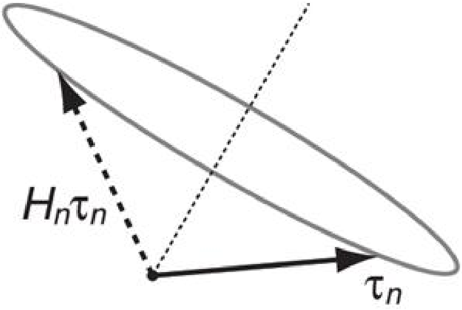
Isotropic Hinge Model

- The hinge rotation matrices are assumed to scatter the direction of the PMD vector uniformly across the sphere.
- Has been used extensively because it allows analytical predictions.
- While convenient, theoretical and experimental studies show this to be an unrealistic assumption.



Anisotropic Hinge Model

- Hinges produce a random rotation about a static axis.
- More consistent with experimental studies (but still not perfect).
- Statistics are more complicated, and cannot obtain the PDF of DGD analytically.

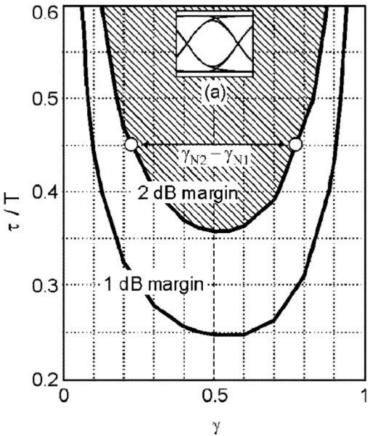


Power Margin

- 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.

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.
- $\gamma_{N1}(\tau)$ and $\gamma_{N2}(\tau)$ denote the boundries of the outage region for a given τ.
- It is only the distance between the boundries $(\gamma_{N2} - \gamma_{N1})$ that enter into the P_{out} calculation.



This outage map is based on the required OSNR to achieve a BER of 10^{-9}

Computing P_{out} Via the Outage Map Approach

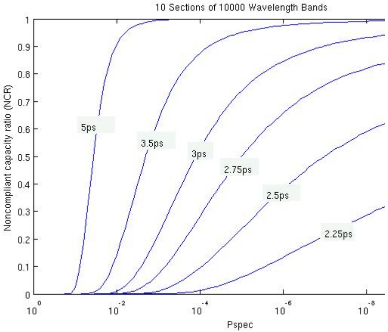
- The system's robustness to PMD is quantified by the outage probability P_{out}.
- P_{out} is the probability that the effects of PMD will induce an error.
- P_{out} can extend down to 10^{-9}, so direct measurements are unfeasible.
- PMD is fully characterized by γ and τ and the PMD induced OSNR penalty $\epsilon_{[dB]}$ can be expressed as a function $f(\tau, \gamma) = \epsilon_{[dB]}$
- We can compute the outage probability as an integral of the joint probability density function (PDF(τ, γ)) of the PMD over the outage map, where the outage region is considered to be when the PMD margin exceeds the power margin. $(\epsilon_{[dB]} > N_{[dB]})$
- Since τ and γ are statistically independant,

Noncompliant Capacity Ratio

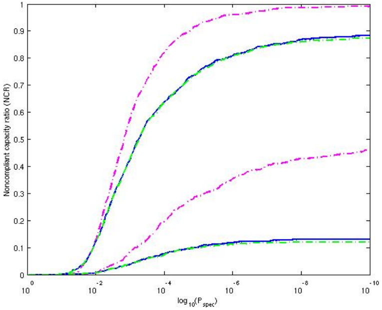
- Outage probabilities are required to be extremely rare, on the order of minutes, or seconds, per year.
- The precise value, specified by the designer, is called the outage specification (P_{spec}).
- Any wavelength band whose calculated outage probability (P_{out}) exceeds P_{spec} is then said to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

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

Results and Conclusions



The NCR as a function of Pspec with 40Gb/s NRZ modulation for the isotropic hinge model. The results are for links of 10 sections. The mean DGD of each link is indicated on each curve.



The NCR for the isotropic model (purple, dot-dashed lines), the anisotropic model with a uniform splitting ratio (solid blue lines), and that with a non-uniform splitting ratio (solid green lines). The top three lines are for links of 10 sections with mean DGD of 3.0 ps; the bottom three for links of 6 sections with mean DGD of 2.5 ps.

References and Acknowledgements

This work was funded by the National Science Foundation CSUMS program, grant numbers 0802994 and 0802964. Special thanks go to Dr. John Ringland, Dr. Joaquin Carbonara, Dr. Jinglai Li, and especially to our mentor Dr. Gino Biondini.

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