Polarization Activity Monitoring of an Aerial Fiber Link in a Live Network

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Agenda

• Introduction
• Optical Network/System Hierarchy
• Optical Fiber Basics
• Polarized Light Overview
• Field Measurement of Polarization Dynamics and Correlation to Environmental Conditions
• Next steps
Optical Network and System Overviews
Optical Network

- All Optical to the Access Nodes
- Wavelength Reconfigurable Optical Add/Drop Multiplexer (ROADM)
• All Long-haul and Metro nodes are ROADMds
• Wavelength transport - C-band ~1550nm
• Systems have multiple channels/wavelengths/colors separated by increments
- Multi-degree node – any-to-any direction
Example Optical Long-Haul Network
Long-Haul (long distance, LD) Network

- 90+ % rail-plowed – 1986-1994
- Hut-spacing 25km-45km
- Direct-Buried Cables – low fiber-count (24f – 48f)

- High traffic – systems have Eighty Eight 100G channels (wavelengths)
Metro ROADM Network
Access Passive Optical Network (PON)
Fiber Challenges

- Challenges are different, depending on which network (LD, metro, access)
  - line rates, modulation techniques, wavelength density, etc.

- Access Network (power meter)
  - Fiber loss
  - connector loss

- Metro Network (power meter, return loss, OTDR)
  - Fiber loss
  - Connector loss
  - Number /quality of splices – return loss
Fiber Challenges - LD network

- Long-Haul Network (power meter, return loss, OTDR, chromatic dispersion, PMD)
- Many challenges minimized by coherent modulation (phase-shift keyed)
  - Amplitude and phase known
- Mixed fiber types
  - Splice loss/mismatch – reflection
  - High power amplification (Raman) – nonlinearities
- Number/quality of connectors (reflected power/loss)
- Extra-Long distance spans (high attenuation)
- Polarization-related impairments
Optical Fiber Basics
Fiber Strand Cross Section

**Inner Acrylate coating**

- 190 µm dia
- Low modulus of elasticity (soft) protective coating;
- Prevents bending loss;
- No light-guiding

**Outer Acrylate coating**

- 245 µm dia
- High modulus of elasticity (hard) protective coating;
- Prevents mechanical damage such as scratches, chips, abrasion, etc.;
- Loss of this coating will cause high bending loss esp at low temperatures;
- Loss of this coating also allows stress concentrators (grit) in contact with the soft coating which erodes easily
- No light-guiding, only protection

**Ink**

- 250 µm dia
- Color only, no protection

**Fiber strand Core + Cladding**

- 125 µm dia

**Core**

- ~ 10 µm dia

**Fiber**
Dispersion in Single-Mode Optical Fiber

**Intra-modal Dispersion, or Chromatic Dispersion (CD)**
Different wavelengths travel at different speeds - linear

**Polarization Mode Dispersion (PMD)**
Different polarization modes travel at different speeds - nonlinear
Optical Fiber Attenuation

- **Conventional single-mode fibers** (older, pre-2000)
  - O-Band: 1260-1360 nm
  - C-Band: 1530-1565 nm
  - E-Band: 1360-1460 nm
  - O-H absorption

- **Low Water Peak Fiber**

- **Rayleigh scattering**

- **Infrared absorption**

- **CWDM**
  - S-Band: 1460-1530 nm

- **DWDM**
  - U-Band: 1625-1675 nm
  - L-Band: 1530-1565 nm
  - C-Band: 1300-1550 nm
Polarization of Light
Overview
Polarization

• Description of polarized light (qualitative & quantitative)

• Generating and modifying polarization

• Polarization in optical fiber
Basic Description of Light

Three basic parameters describe light:

- **Wavelength**: $\lambda$ (color)
- **Intensity**: $I$ (brightness)
- **Polarization state**: $S$ (subtle)

The polarization state is defined by the path of the E-field oscillation.
Linear: Orientation of the plane of vibration

Elliptical: Ellipticity and orientation of the major axis

Abbreviations:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>H (horizontal)</td>
<td>+45 (+45° w/horizontal)</td>
</tr>
<tr>
<td>V (vertical)</td>
<td>-45 (-45° w/horizontal)</td>
</tr>
<tr>
<td>RHC</td>
<td>(right-hand circular)</td>
</tr>
<tr>
<td>LHC</td>
<td>(left-hand circular)</td>
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</tbody>
</table>
It only takes 2 numbers to describe the state of polarization of light.

Ellipticity $\chi$

$$\tan \chi = \pm \frac{b}{a}$$

Handedness

Orientation of major axis $\psi$

State of polarization is commonly described in one of two ways: Stokes vectors/Mueller matrices and Jones vectors/matrices
Phase: $\Delta \phi = \pi/2$

Phase (retardance) between H and V determines ellipticity ($\chi$).

Relative amplitudes $A_x$ and $A_y$ determine axis orientation ($\psi$).
Measurement of Light: Stokes Vectors

\[ \hat{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \]

- \( S_0 \) = Total intensity of light (typically “normalized” (\( S_0=1 \))
- \( S_1 \) = Amount of light that is Horiz. or Vert. (linear)
- \( S_2 \) = Amount of light that is \( \pm 45^\circ \) (linear)
- \( S_3 \) = Amount of light that is RHC or LHC

Stokes vectors describe the state of polarization using **intensity**

- Easy to measure (based on observables)
- Includes “unpolarized” light
- Includes the total intensity of the light
Stokes Vectors Quiz

\[ \hat{\mathbf{S}} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \]

- Normalized intensity
- Horiz. or Vert. (linear)
- ±45° (linear)
- RHC or LHC

\[ \hat{\mathbf{S}} = \begin{pmatrix} 1 \\ \cos 2\chi \cos 2\psi \\ \cos 2\chi \sin 2\psi \\ \sin 2\chi \end{pmatrix} \]

**General**

**QUIZ: What kind of polarization states do we have here?**

\[ \hat{\mathbf{S}}_1 = \begin{pmatrix} 1 \\ 0.5 \\ 0.866 \\ 0 \end{pmatrix} \]

\[ \hat{\mathbf{S}}_2 = \begin{pmatrix} 1 \\ 0.482 \\ 0.835 \\ 0.286 \end{pmatrix} \]

\[ \hat{\mathbf{S}}_3 = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \]
The Poincaré sphere:
- Plots Stokes vectors
- Linear states on the equator
- Elliptical states off the equator
- The poles are RHC and LHC

\[ \hat{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \]

- Normalized intensity
- Horiz. or Vert. (linear)
- ±45° (linear)
- RHC or LHC

Poincaré Sphere – Polarization Mapping
Field Measurement of Polarization Dynamics and Correlation to Environmental Conditions

Ongoing
Measurement Drivers

- Traffic interruptions measured on several Long-Haul routes
  - No outages, protection switches occurred
- Investigate polarization dynamics on different constructions
  - Buried, Aerial, Metro, Central Office (craft)
  - Large Temperature fluctuations (NE), Lightening (SE)
  - Train, subway, traffic, etc
- Started study with Lightening rich areas (SE)
Optical Ground Wire (OPGW)

- Unexplained protection switches witnessed on several Long-Haul routes containing OPGW in the SE.
- Lightening can temporarily change the index of refraction (Kerr effect) as a result of the change of $\varepsilon$. 
Lightening Map

National Lightning Detection Network
2005 - 2014

VAISALA
## OPGW route candidates

<table>
<thead>
<tr>
<th>Route</th>
<th>Length [km]</th>
<th>Reported [flashes/km²/yr]</th>
<th>Expected lightning strikes within 0.5km radius of link [flashes]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orlando, FL to Tallahassee, FL</td>
<td>513</td>
<td>8.1</td>
<td>4155</td>
</tr>
<tr>
<td>Pensacola, FL to New Orleans, LA</td>
<td>336 (130km OPGW)</td>
<td>9.8</td>
<td>3293</td>
</tr>
<tr>
<td>Memphis, TN to Charlotte, NC</td>
<td>992</td>
<td>4.8</td>
<td>4762</td>
</tr>
<tr>
<td>West Orange, NJ to Harrisburg, PA</td>
<td>304</td>
<td>2.3</td>
<td>699</td>
</tr>
<tr>
<td>Indianapolis, IN to Louisville, KY to Nashville, TN</td>
<td>480</td>
<td>6.0</td>
<td>2880</td>
</tr>
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The exact distance a strike can be from the link for the resulting change in SOP to be within our sensitivity is unknown. We use 0.5km as a coarse estimate and assume that whatever the actual distance, it will be constant across all links.
Optical loopback installed at Tallahassee.

Round-Trip Delay

Polarimeter installed at Orlando with a PC with LAN access
Measurement Setup
Orlando-Tallahassee SOP (4/16-8/16)
Orlando-Tallahassee SOP

• Set up turn on in April 2016
  – Collecting data ~ 55% of time

• Observation
  – Majority of transients within 500 krad/s
  – Some correlations made with lightening events
    • Lightening magnitudes vs SOP transients being analyzed
  – Measurements are ongoing
  – End Date TBD (end of lightning season in FL, Oct. – Nov.)
• Clusters of SOP transients measured
• Spacing between transients in cluster is roughly constant at ~16ms
• Pairs of each transient are ~3ms (RTD of events)
New Orleans – Pensacola SOP (8/16-2/17)

- RTD shows distance of events 278.1 km +/- 0.66km from N.O.
Taking the 550 measurements starting Aug. 18 we average the autocorrelations of the set to observe a single peak at about 331.12km

Error is due to index of refraction uncertainty
New Orleans – Pensacola SOP (8/16-2/17)

Observations

- Cause Unknown – mechanical?
- Hours exist where many triggers occur, followed by quiet hours.
  - We are investigated equipment PM data for patterns
- Observed angular velocities exceed 600krad/s
- Events originate near the test site in downtown New Orleans.
  - Optical distance from test site and map of fiber plant have us suspecting the North Rampart St. construction.
- Trigger settings adjusted to 10°@100krad/s
  - This should filter out the vast majority of the static transients so that we can proceed with monitoring for lightning induced transients.