An advanced Dark Fiber Monitoring System for Next Generation Optical Access Networks

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Outline

› Introduction
› Operation Principle
› Experimental validation
› Conclusions
Introduction
Next generation optical access (NGOA)

NGOA:
- cover large service areas
- high-capacity
- support multi-service environment

Introduction
“Ring-and-Spur” Long-Reach PON

“Ring-and-Spur” Long Reach PON, a promising solution for NGOA

A fault occurs: a large amount of data will be lost

Monitoring: real-time information of fault location

- Consolidation of metro and access networks, feeder fiber can be up to 100 km
- Reduces the number of COs and active optical interfaces

Introduction
Optical Time Domain Reflectometry (OTDR)

**OTDR**
Optical Time Domain Reflectometry

- P2P characterization
- Loss, RL, attenuation coeff…
- 1m or 30m resolution
- 30-40 dB dynamic range

Limitations:
- Amplifiers on the ring can only work on **C-band**, OTDR signals (**U-band**) will be blocked
- Lack of dynamic range
- Long measurement time (3 minutes)

http://www.thefoa.org/tech/ref/quickstart/OTDR/
Outline

› Introduction
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“Ring and Spur” LR-PON monitoring
Dark fiber monitoring scheme[3]

- Dark fiber monitoring
  - Dark fiber: fiber deployed in the same cable but not carry data
- Bi-directional multi-wavelength TRA (BD-nλ-TRA) approach

TRA based dark fiber monitoring

Feeder Cable layout

M. Cen, et al, ECOC 2014
M. Cen, et al, OFC 2015

- Cover major faults
- One can choose any monitoring λ, power
- No traffic interruption

TRA: transmission reflection analysis
New monitoring techniques (1)
Transmission Reflection Analysis (TRA)\[^{[4]}\]

Basic principle: It is based on the unique relationship between the transmitted power \((P_T)\) and the backscattered power \((P_B)\) at a certain fault location\[^{[5]}\].

1. Only for non-reflective events (e.g. fiber bending) localization;
2. Low accuracy at remote end

\[
Z_p = \frac{1}{-2\alpha} \times \ln \left( \frac{P_{B1} \cdot (1 - e^{-2\alpha L}) + P_{T1}^2 \cdot e^{-2\alpha L} - 1}{P_{T1}^2 - 1} \right)
\]

SLD: super luminescent diode

New monitoring techniques (2)
Multi-wavelength (e.g., $2\lambda$) - TRA (newly proposed)\[^6\]

$$R_{n1} = \frac{P_{B\lambda 1}}{P_{B01}} = \frac{R_{ray1}(z_p) + T_1^2(z_p) \cdot RL + [R_{ray1}(L) - R_{ray1}(z_p)] \cdot t_n^2}{R_{ray1}(L)}$$

$$R_{n2} = \frac{P_{B\lambda 2}}{P_{B02}} = \frac{R_{ray2}(z_p) + T_2^2(z_p) \cdot RL + [R_{ray2}(L) - R_{ray2}(z_p)] \cdot t_n^2}{R_{ray2}(L)}$$

Able to localize reflective events (e.g. fiber breaks)

$R_{ray(2)}$, $T_{1(2)}$ are changed with $\lambda$

2 equations, 2 unknown variables ($z_p$ and $RL$)

New monitoring techniques (3)
Bi-Directional TRA (newly proposed)\[7\]

\[
R_{n1} = \frac{P_{B1}}{P_{B01}} = \frac{R_{ray}(z_p) + T^2(z_p) \cdot RL + [R_{ray}(L) - R_{ray}(z_p)] \cdot t_n^2}{R_{ray}(L)}
\]

\[
R_{n2} = \frac{P_{B2}}{P_{B02}} = \frac{R_{ray}(L-z_p) + T^2(L-z_p) \cdot RL + [R_{ray}(L) - R_{ray}(L-z_p)] \cdot t_n^2}{R_{ray}(L)}
\]

Localization Accuracy Analysis

Simulation results

- Bi-directional configuration provides much better localization accuracy at the remote end (localization error: from 5.3km to 0.1m; STD: from 15km to 5m)
“Ring and Spur” LR-PON monitoring
$n\lambda$-TRA (Bi-directional) + Dark fiber\[3\]

2 × 2 OS → bi-directional measurement in the ring system

› Reflective events (break, connector mismatch): $2\lambda$-BD-TRA
› Non-reflective events (bending): $1\lambda$-BD-TRA
“Ring and Spur” LR-PON monitoring

Monitoring procedure

\[ \Delta P_{T1(2)} = P_{T01(2)} - P_{T1(2)} \]

- 2 SLDs (\(\lambda_1 > \lambda_2\)) are triggered for measuring \(P_{T1}\) and \(P_{T2}\)
- If \(P_{T1}\) and \(P_{T2}\) are null:
  - Yes: 2\(\lambda\)-BD-TRA is applied for localization by triggering 2 SLDs
  - (cable cut)
- Otherwise:
  - No: \(\Delta P_{T1} < \Delta P_{T2}\)?
  - Yes: 2\(\lambda\)-BD-TRA is applied for localization by triggering 2 SLDs
  - (connector mismatch)
  - No: The fault is identified and localized

A fault occurs in the feeder cable ring
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› Experimental validation
› Conclusions
Experimental validation
Comparison between OTDR and 2λ BD-TRA

$L [\text{km}]: 56.02; z_p [\text{km}]: 0, 1.727, 26.42, 51.13, 56.02;$
Event: fiber break, fiber bending

Case of fiber break (2λ-BD-TRA, 1550nm+1310nm):

<table>
<thead>
<tr>
<th></th>
<th>$Z_{p1} [\text{km}]$</th>
<th>$Z_{p2} [\text{km}]$</th>
<th>$Z_{p3} [\text{km}]$</th>
<th>$Z_{p4} [\text{km}]$</th>
<th>$Z_{p5} [\text{km}]$</th>
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</thead>
<tbody>
<tr>
<td>OTDR</td>
<td>0</td>
<td>1.727</td>
<td>26.42</td>
<td>51.13</td>
<td>56.02</td>
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<tr>
<td>TRA</td>
<td>-0.0015</td>
<td>1.7264</td>
<td>26.4454</td>
<td>51.1227</td>
<td>56.026</td>
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<tr>
<td>Difference</td>
<td>1.5m</td>
<td>&lt;1m</td>
<td>25.4m</td>
<td>7.3m</td>
<td>6m</td>
</tr>
</tbody>
</table>

Case of fiber bending (1λ-BD-TRA, 1550nm):

<table>
<thead>
<tr>
<th></th>
<th>$Z_{p1} [\text{km}]$</th>
<th>$Z_{p2} [\text{km}]$</th>
<th>$Z_{p3} [\text{km}]$</th>
<th>$Z_{p4} [\text{km}]$</th>
<th>$Z_{p5} [\text{km}]$</th>
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<td>1.727</td>
<td>26.42</td>
<td>51.13</td>
<td>56.02</td>
</tr>
<tr>
<td>TRA</td>
<td>0.015</td>
<td>1.7237</td>
<td>26.4306</td>
<td>51.1233</td>
<td>56.002</td>
</tr>
<tr>
<td>Difference</td>
<td>15m</td>
<td>4.3m</td>
<td>10m</td>
<td>6.7m</td>
<td>18m</td>
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</table>
Comparison between OTDR and $\lambda$ BD-TRA

Discussion

Comparison between OTDR and $\lambda$-BD-TRA for the LR-PON monitoring:

<table>
<thead>
<tr>
<th></th>
<th>OTDR</th>
<th>$\lambda$ BD-TRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement time</td>
<td>3 minutes</td>
<td>3 seconds</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>30m</td>
<td>1m(best)/60m(worst)</td>
</tr>
<tr>
<td>Light source</td>
<td>Time modulated</td>
<td>Unmodulated CW</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>&lt;45dB</td>
<td>&gt;60dB</td>
</tr>
</tbody>
</table>

$n\lambda$ BD-TRA provides better localization performance than OTDR
Conclusion and future works

Conclusion:
› Able to identify and localize a single event along the feeder ring
› The dark fiber concept — one can choose any monitoring wavelength; Monitoring can be performed without any traffic interruption
› Newly proposed TRA based technique — greatly save the monitoring time (from a few min to a few seconds); improve the dynamic range (>60dB); requires simpler light source

A fast and simple monitoring solution for LR-PON system

Future works:
› Cover distribution section monitoring
Acknowledgement

Thank you!

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Localization Accuracy Analysis
Analysis Methodology

- Powermeter inaccuracy: $\zeta_1$ and $\zeta_2$ (0.1%)
- Measurement range: $P_B \pm P_B \cdot \zeta_1$ and $P_T \pm P_T \cdot \zeta_2$
- A uniform distribution of $P_B$ and $P_T$ within the measurement ranges (10000 samples)
- Calculate the expected localization error and corresponding STD
\( \Delta P_T \) comparison

- the bending loss is mainly caused by the fiber refractive index distortion. The shorter the wavelength, the better the optical mode confinement in the fiber. Therefore light with shorter wavelength will lead to a smaller \( \Delta P_T \). In opposite, regarding a connector mismatch (perpendicular to the fiber axis) whose loss is related to the mode filed diameter (MFD), light with shorter wavelength will generate a larger \( \Delta P_T \).
Connector mismatch

It should be noted that the functionality of detecting and localizing a connector mismatch in a dark fiber is not dedicated to the monitoring of the data carrying fibers. By analyzing the transmitted power, one can identify whether the detected fault is shared among all the data carrying fibers (cutting, bending) or not (connector mismatch). Based on this information, the operator could proceed forward, either by localizing the cable cut or bending for the data carrying fibers or by fixing the dark fiber connection at the localized location. Moreover, with the increased bandwidth demand, the dark fibers deployed in the cable may be used for data transmission fiber in future. With this in mind, it is important to evaluate the quality of the dark fiber before using it for data transmission.