Network Optimization of Optical Performance Monitoring

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Outline

- Motivations
- Advanced Monitoring Techniques for point-to-point link
  - OSNR Monitoring
  - Chromatic Dispersion Monitoring
  - Multi-impairment Monitoring
- Optimization of performance monitoring networks
  - Optimization of Fault-diagnosis with Minimum Probing
  - Algebraic Monitoring Network
  - Other related works
- Conclusions
Optical Performance Monitoring

- Definition: Physical layer monitoring of the signal quality, for the purpose of determining the health of the signal in the optical domain

Applications:  

<table>
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<th>Examples:</th>
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</table>
| Signal quality characterization | - Relating OSNR with BER  
|         | - Early signal degradation alarm               |
| Fault management            | - Fault detection, localization, and isolation  
|         | - Resilience mechanism activation              |
| Active compensation         | - Dynamic CD + PMD monitoring and compensation  |
| Quality of service (QoS) provisioning | - SLA fulfillment verification                 |

Wish List for the Enhancements of OPM

- higher dynamic range;
- higher sensitivity;
- robustness to various effects;
- multi-impairment monitoring; and
- lower cost.

But how?

⇒ Optimization of Performance Monitoring System
**OSNR monitoring module**

\[
OSNR(dB / 0.1nm) = \frac{P_{\text{sig,in}} \cdot NEB_f}{P_{\text{ASE,in}} \cdot 0.1nm} \\
= \frac{(1 - r) \cdot NEB_f}{[r(1 - D_{\text{sig}}) - (1 + D_{\text{sig}})] \cdot 0.1nm}
\]

\[
P_{\text{max}}/P_{\text{min}} = \frac{(P_{\text{max}} - P_{\text{min}})}{(P_{\text{max}} + P_{\text{min}})}
\]

when noise is absent

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**Proposed OSNR Monitoring Module**  
(Ref: Y.C. Ku et al., OFC 2006)

- **Bandpass filter**
- **Isolator**
- **Polarization scrambler**
- **Phase Mod**
- **Power Meter**

**Graphs:**
- Transfer function (dB)
- Output power vs. V_{Phase Mod.}
Experimental results: 10Gb/s, back-to-back

Without PMD:
- Monitoring error < 0.25 dB
- 40-dB monitoring dynamic range

With PMD:
- Influence of DGD
  - reference OSNR 25 dB/0.1nm
  - Monitoring error < 0.25 dB

Graphs showing OSNR by proposed scheme and monitoring error as functions of OSNR by OSA and DGD, respectively.
Experimental results: 10Gb/s, 150km, w. ~1.5ps PMD

- Influence of **chromatic dispersion** and **transmitted power**
  - An EDFA was added after each 50-km SMF span
  - EDFA output power 1 or 10 dBm

![Graph showing OSNR vs. Distance for different output powers and methods.](attachment:graph.jpg)
Experimental results: 10Gb/s, back-to-back, w/ polarized noise

- Influence of partially polarized noise
- Worst case: DOP=99.69%
Chromatic Dispersion (CD) Monitoring
Previous work on chromatic dispersion monitoring

- Clock phase difference monitoring
  - Pros: No need to modify transmitter, highly sensitive
  - Cons: requires high-speed electronics


We propose to use a birefringent fiber loop (BFL) to realize a simple, polarization insensitive CD monitoring scheme without transmitter side modification, and demonstrate in NRZ system

Ref.: Y.C. Ku, et. al., OFC 2006
Proposed Dispersion Monitoring Module based on BFL

- Measure RF power at dispersion dependent frequency dip ($f_{RF}$) produced by birefringent fiber loop (BFL)

$$P \propto \sin^2 \left( \frac{\varphi_\Omega + \varphi_- \Omega}{2} \right) = \sin^2 \left( \frac{\pi \lambda^2 f_{RF}^2}{2} D \right)$$

$$f_{RF} = \frac{\Omega}{2\pi} = \frac{1}{2\tau}$$

Ref.: Y.C. Ku, et. al., OFC 2006
Experimental Result

- Measured unambiguous monitoring range: 1500 ps/nm for 10-Gb/s NRZ signal
- In principle, monitoring range can reach $c/2\lambda^2f_{RF}^2 = 2497$ ps/nm
Multi-impairment Monitoring
Multi-impariment monitoring - Delay Tap Asynchronous Waveform Sampling

Combines asynchronous sampling with two tap delay lines, so that each sample point comprises two measurements (x and y), separated by a fixed time corresponding to the delay length.

Application of asynchronous sampling in PMD monitoring

\[ m = \frac{\text{number of sample points falling on the left and the bottom edges}}{\text{total number of sample points on the scatter plot}} \]

- The proportion of sample points on the left and bottom edge is used as the effective parameters to evaluate PMD value.
Application of asynchronous sampling in misalignment monitoring for RZ-OOK

The increasing dispersion and rotation of the sample points on the diagonal can serve as effective parameters to evaluate alignment status.

\[ d = \frac{1}{n} \sum_{i} \sqrt{x_i^2 + y_i^2} \sin \left( \frac{\pi}{4} - \arctan \left( \frac{y_i}{x_i} \right) \right) \]

\[ t = \frac{1}{n} \sum_{i} \arctan \left( \frac{y_i}{x_i} \right) \]

\[ d: \text{ deviation from diagonal line} \]
\[ t: \text{ average angle of sample points} \]

Ref.: Y.C. Ku, et. al., ECOC 2006
Experimental results

- Sign and amount of misalignment can both be estimated
Correlation of Monitored Parameters

- Monitored parameters may be correlated.
- The monitoring schemes need to be able to differentiate different possible impairments

Table 2/G.697 – List of correlation between the underlined impairments and monitoring parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Total power</th>
<th>Channel power</th>
<th>Channel wavelength</th>
<th>OSNR</th>
<th>Q-factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variation of attenuation</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Frequency (or wavelength) deviation from nominal</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Optical channel power changes due to gain variations</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Ref: ITU-T G.697 Optical monitoring for DWDM systems

Question:
- Can we derive one parameter based on the measurement of the other parameters?
- How about other dimensions of correlations, e.g. spatial & temporal?
Optimization of Performance Monitoring System

Consider a performance monitoring system $S_{PM}$ that is formed by all the monitoring devices in a network and the corresponding measurements.

Optimization of $S_{PM}$:
1. the minimum number of monitors required
2. the optimal locations of the monitors – monitor placement problem
3. the minimum number of measurements needed

Issues:
- static network vs. dynamic (reconfigurable) network
- distributed vs. centralized monitoring

CAPEX
OPEX
Centralized vs. Distributed OPM

- Monitoring
- Diagnosis

- Distributed monitoring / centralized diagnosis
- Centralized monitoring / centralized diagnosis

Single monitoring point for the whole network
Number and Placement of OPM

Optimization of Placement and Amount of OPM needed

► One-monitor-per-link/component is not optimum if we consider
  ♦ failure probability of link/component
  ♦ scalability with the network size
  ♦ amount of redundant alarm

1. Channel-Based: Design Based on Established Lightpaths

E.g.

![Alarm matrix computation](image)

Optimal monitor placement: monitor

- In-service channel performance based
- Reduce monitor number considerably
- For static network only

Number and Placement of OPM

2. Network-Based: Design Based on Network Topology

E.g. Break down a network into a number of “monitoring cycle” and assign a monitor to each, using an extra supervisory wavelength to probe the health of the cycle.

Ref: Hongqing Zeng et al, “Monitoring cycles for fault detection in meshed all-optical networks”, in Proc. ICPPW’04, pp. 434-439

- Suitable for dynamic networks
- Does not measure in-service channel quality
- Reduce monitor number considerably
- Extra wavelength needed

Cycle finding algorithm
Scalable Network Diagnosis for All-Optical Networks via Group Testing Over Graphs

Analogy: *fake coins problem*

Objective: to minimize the number of measurements to identify the fake coin(s) that are of less weight

Asymptotically Optimal Run-Length Probing Schemes via an Information Theoretic Approach

Guidelines for Fault Diagnosis Algorithms

- The total number of probing is approximately equal to the entropy of the network state
- Each probe should provide approximately 1 bit of state information
Network Diagnosis – an algebraic approach

Objective: To find an efficient way to determine the quality of different paths, so that it can be used as a metric for path computation in the network layer for channel setup.

For example:
- Two existing monitoring channels $c_1$ and $c_2$
- New request to setup $c_3$
- NO estimation

Network diagnosis that explores the spatial correlation to minimize the number of monitors.

Linear expressions of optical impairments

- **Noise Figure (NF)**

\[
NF_{\text{overall}} = NF_1 + \frac{NF_2}{G_{c2}} + \frac{NF_3}{G_{c3}} + \ldots + \frac{NF_k}{G_{ck}}
\]

- **Chromatic dispersion (CD)**

\[
CD_{\text{overall}} = \Delta \lambda \cdot (L_1 \cdot D_1 + L_2 \cdot D_2 + \ldots + L_k \cdot D_k)
\]

- **Polarization-mode-dispersion (PMD)**

\[
PMD_{\text{overall}}^2 = \sum PMD_{\text{fiber}}^2 + \sum PMD_{\text{component}}^2
\]

Overall impairment for all paths can be derived from impairments of individual fiber link and component
A sample network

\[ x_1 - x_5 : \text{Impairments on links} \]
\[ x_6 - x_9 : \text{Impairments on nodes} \]
\[ c_1 - c_3 : \text{3 probing channels} \]

: Node with monitoring module

Accumulated impairment of \( c_1 \):
\[ x_4 \]
Accumulated impairment of \( c_2 \):
\[ x_3 \]
Accumulated impairment of \( c_3 \):
\[ x_2 + x_8 + x_3 \]

(The monitoring module contain both monitoring source and monitoring detector.)
Problem formulation

\( M: \text{Monitoring Matrix} \)

\( x: \text{individual impairment} \)

\( y: \text{Accumulated impairment} \)

For the previous example, total 9 impairment variables to be determined and 2 monitoring modules are used Æ 9:2

Assumption: monitoring modules are able to monitor different probing channels from all ports by time division manner or by proper labeling

Q: What is the minimum number of monitoring modules and where should they be placed?
Bus & Ring networks

Diagram showing the connection of nodes X1, X2, X3, X4, X5, and X6 with edges labeled c1L, c2L, c2R, and c1R.
Two-link-connected network

\[ \text{Impairment}(c) = \text{Impairment}(c_{\text{green}}) - \text{Impairment}(p_{\text{red}}) - x \]
Summary of Algebraic Network Diagnosis

- Proposed a novel algebraic approach of monitoring optical impairments in both un-directional nodes and links.

- Proved that two monitoring modules are necessary and sufficient to support our monitoring scheme in two-link-connected network.

- For every node that becomes a leaf node after removal of all leave nodes in the original network, installing one monitoring module at it is necessary and sufficient to support the proposed probing scheme.

- For general networks with bridges, first transform the network to a tree-like structure and then solve it by “divide-and-conquer” method.

- With the probing scheme, any single-fault can be located in the whole network.
Intelligent Fault Diagnosis for Optical Networks: Detection, Isolation and Prognosis

Two fault-diagnosis formulation approaches:
• model-based
• data-driven

YG Wen, MIT

WOCC 2008

Centre for Advanced Research in Photonics
The Chinese University of Hong Kong
Conclusions

- OPM in next-generation high-speed transparent reconfigurable networks is essential.

- Enhancements of OPM, including higher dynamic range, higher sensitivity, robustness to various effects, and multi-impairment monitoring, are desirable to make the OPM system more effective.

- By exploring the correlation of different spatial or time domain information, it is possible to further enhance the efficiency of OPM.

- Some works on the Optimization of OPM network to derive theoretical bounds for the min. number of monitoring module or the number of probing are presented.
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The End