Multicasting with Physical Layer Constraints in Metropolitan Optical Networks with Mesh Topologies

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Outline

• Introduction

• Physical Layer Impairments

• Multicasting in Transparent Networks

• Multicast Protection

• Conclusions and Future Work
Introduction-
Optical Networks

• Optical Network:
  • Telecommunications network with transmission links that are optical fibers, “intelligent” optical switching nodes, and with an architecture that is designed to exploit the unique features of fibers.

• Advantages of Optical fibers:
  • Huge bandwidth capability (e.g., 25 THz)
  • Low attenuation loss,
  • Extremely low bit-error rates,
  • Low cost,
  • Light weight,
  • Strength and flexibility,
  • Immunity to noise and electromagnetic interference
  • Security and privacy
Introduction -
Evolution of Optical Networks

- Point-to-point Networks:
  - Fiber transmission links were used as a direct substitute for copper, with the fibers terminating on electronic equipment.
  - Due to electronic equipment only a small fraction of the potentially available bandwidth could be used.

- WDM Networks:
  - The capacity of a fiber link is dramatically increased.
  - A number of wavelengths is multiplexed for simultaneous transmission within the same fiber.
Introduction—Optical Networks

- **Optical Network:**
  - Telecommunications network with transmission links that are optical fibers, “intelligent” optical switching nodes, and with an architecture that is designed to exploit the unique features of fibers.

- **WDM Optical Network:**
  - The capacity of a fiber link is dramatically increased.
  - A number of wavelengths is multiplexed for simultaneous transmission within the same fiber.
Introduction-
Evolution of Optical Networks

• A typical WDM network cable contains:
  • More than 100 fibers which are used as bidirectional pairs.
  • Each fiber can utilize 32 to 64 wavelengths of 0.8 nm spacing covering a range of 1260 - 1675 nm
  • Each wavelength transmits at rates of 10 Gbps.

• A denser WDM network:
  • 80 to 160 wavelengths per fiber
  • Each wavelength transmits at rates of 40 or 100 Gbps
  • Future DWDM networks expected to increase to 320 wavelengths per fiber.
Introduction-
Evolution of Optical Networks

a. Opaque Network:
• All switching and processing of the data is handled by electronic switch fabrics.
• The optical signal carrying traffic undergoes an optical-electronic-optical (OEO) conversion at every switching node.

q Ads
• Offers full digital regeneration of the signal (re-shape, re-time, re-amplify).
• Any incoming stream can be switched to any available wavelength on any fiber.
• There is no need for end-to-end traffic engineering.
• The control and management of the network is easy.

q Cons
• Limitations in signal bit rate due to electronics.
• Costly network elements.
• Bit rate@protocol/modulation format are not transparent.
Introduction - Evolution of Optical Networks

b. **Transparent Network:**
   - Switching and processing of the data is moved to the optical part of the network
   - **Ads**
     - Eliminates the expensive O-E-O conversions.
     - Signal is transparent to bit rate, signal format, and protocols.
     - Provides high bit rates.
   - **Cons**
     - Physical layer impairments (e.g. noise, dispersion, crosstalk) limit the transmission reach of optical signals.
     - End-to-end engineering of the traffic is required.
     - Difficult control and management functions.
Introduction - Transparent MANs

- **Metropolitan Area Network (MAN)**
  - Spans a metropolitan area, typically tens to a few hundred kilometers.
  - Signal attenuation could be overcome using optical amplifiers, as needed.
  - The noise that these amplifiers introduce can be managed due to the relatively short distances, (short amplifier spans).
  - No dispersion issues due to short fiber lengths
  - High optical signal to noise ratio can be preserved.
QoT -
Physical Layer Impairments

• Quality of Transmission (QoT):
  • The signal must be detectible to the receiver end

  • QoT is affected by:
    • Amplifier Spontaneous Emission (ASE) Noise
    • Incoherent crosstalk
    • Fiber nonlinearities (FWM, SFM, XFM, ....)
    • Dispersion (CD, Intermodal dispersion, PMD)
    • Component Aging
    • Attenuation
    • PDL/PDG, etc
Physical Layer System Modeling

- Physical Layer Impairments must be taken into account during the provisioning phase of request.
- Modeling of the physical layer is based on the physical path Q factor that is used to calculate the BER of the system.

\[ Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \]

\[ \sigma_i^2 = \sigma_{th}^2 + \sigma_{shot-i}^2 + \sigma_{ASE-ASE}^2 + \sigma_{s-ASE-i}^2 + \sigma_{RIN-i}^2 + \sigma_{ASE-shot}^2 \]

- This approach assumes a baseline system with various receiver noise terms as well as ASE noise.
- A Q-budgeting approach is used to include:
  - Incoherent crosstalk channel penalty budgeted at 0.8dBQ.
  - Fiber nonlinearities factored at 1 dBQ.
  - PMD budgeted at 0.2 dBQ.
  - Optical filter narrowing penalty budgeted at 0.4 dBQ.
  - Safety margin of 1dBQ included for component aging
QoT-
Physical Layer System Modeling

• This approach enables a network designer to calculate the impact of physical layer effects, in the design of an optical network without the computationally complex time-domain approach.

• A Q threshold is set for a specified BER and the decision to provision a given multicast connection relies on whether we are above or below the threshold.

\[
BER = \frac{1}{2} \text{erfc} \left( \frac{Q}{\sqrt{2}} \right) \approx \frac{e^{-\frac{Q}{2}}}{Q \sqrt{2\pi}}
\]

• Q threshold set at 8.5 dBQ which corresponds to a BER of 10^{-12}
Multicasting - Introduction

- **Multicast Applications**: interactive distance learning, video-conferencing, distributed games, movie broadcasts from studios, etc.

- **Multicast connection**:
  - One-to-many connectivity
  - Light from one source must reach many destinations.
  - In transparent optical networks optical splitters must be used inside the nodes to split the incoming signal to multiple output ports.

![Light-tree diagram](attachment://light-tree.png)
Multicast Capable Architectures

- (MxM) transparent node supporting n wavelengths:
  - The splitter equally splits the optical signal into M parts, where M is the number of outgoing (as well as incoming) ports.
  - $P_{Out} = \frac{1}{M} P_{in}$.
  - Amplifiers are required to re-amplify the signal.
  - ASE noise is added to the signal.
- These power considerations along with other physical layer impairments must be taken into account to:
  - The design and engineering of transparent optical nodes.
  - The multicast routing algorithms.
Multicast Capable Architectures

- Several Multicast Capable Node architectures and Engineering Designs were investigated to determine the impact of the physical layer:
  a. Fixed Txs/Rxs
  b. Tunable Txs/Rxs
  c. Tunable Txs/ Fixed Rxs
  d. Fixed Txs /Tunable Rxs

- Component Insertion Loss

<table>
<thead>
<tr>
<th>Component</th>
<th>Mux/Dmux</th>
<th>VOA</th>
<th>Splitter</th>
<th>SOA</th>
<th>Switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Losses in dB</td>
<td>3</td>
<td>0.5</td>
<td>10*log(fan out)</td>
<td>0.6</td>
<td>1</td>
</tr>
</tbody>
</table>
Multicast Capable Architectures

• **Worst case scenario:**
  - The maximum insertion loss a signal encounters passing through the maximum degree node.

• **Components:**
  - **Amplifiers (EDFAs):**
    - Post-Amplifiers: Compensate for the node losses and their gain is set for the worst case scenario with an output power of +7dBm.
    - Pre-Amplifiers: Preceding the fiber span to compensate for the fiber losses that are set at 0.3dB/Km. Output power is +7dBm.
    - Noise Figures are based on realistic device specifications.

<table>
<thead>
<tr>
<th>Gain in dB</th>
<th>NF</th>
</tr>
</thead>
<tbody>
<tr>
<td>G&lt;13</td>
<td>7</td>
</tr>
<tr>
<td>13&lt;G&lt;15</td>
<td>6.7</td>
</tr>
<tr>
<td>15&lt;G&lt;17</td>
<td>6.5</td>
</tr>
<tr>
<td>17&lt;G&lt;20</td>
<td>6</td>
</tr>
<tr>
<td>G&gt;20</td>
<td>5.5</td>
</tr>
</tbody>
</table>

**Variable Optical Attenuators (VOAs):**
Required to equalize the individual total input powers to the post amplifiers and signals are attenuated for the worst case scenario.
Multicast Capable Architectures

**Node Architectures:**

- **Fixed Tx/Rx:** The number of transmitters/receivers for each source/destination node is equal to the number of wavelengths times the degree of the node.

- **Tunable Tx/Rx:** The number of transmitters/receivers for each source/destination node is equal to the number of wavelengths.
Multicast Capable Architectures

• **Tunable Tx/Rx case:**
  - Switches added at the Tx/Rx can add/drop 50% of the total number of wavelengths in the network.
  - The size of the switches is proportional to the number of wavelengths and the fan-out of the node.
  - Insertion loss of switches depends on their size.

<table>
<thead>
<tr>
<th>Size</th>
<th>Switches Losses in dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>X&lt;25</td>
<td>1</td>
</tr>
<tr>
<td>25&lt;X&lt;36</td>
<td>1.5</td>
</tr>
<tr>
<td>36&lt;X&lt;56</td>
<td>2.2</td>
</tr>
<tr>
<td>56&lt;X&lt;68</td>
<td>3</td>
</tr>
<tr>
<td>68&lt;X&lt;80</td>
<td>3.7</td>
</tr>
<tr>
<td>80&lt;X&lt;100</td>
<td>4.5</td>
</tr>
<tr>
<td>X&gt;100</td>
<td>5</td>
</tr>
</tbody>
</table>
Multicast Routing Algorithms

- Several multicast routing algorithms are used for the simulations.
  1. **Minimum Steiner tree heuristic (MST):**
     - Finds the minimum cost tree.
     - The Steiner tree problem is NP-complete when the multicast group has more than two members.
     - Several heuristics have been developed for the Steiner tree problem.
  2. **Optimized Shortest Paths Tree (OSPT):**
     - Aims at decreasing the number of the links utilized by the tree.

<table>
<thead>
<tr>
<th>Step 1</th>
<th>For every destination node of the multicast session, repeat Steps 2 and 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 2</td>
<td>Find the minimum-cost path from source to the destination node.</td>
</tr>
<tr>
<td>Step 3</td>
<td>Update cost = 0 for all the links included in the already-found path.</td>
</tr>
<tr>
<td>Step 4</td>
<td>Merge all the minimum-cost paths together and construct a multicast tree.</td>
</tr>
</tbody>
</table>
3. **Balanced Light-Tree (BLT):**
   - Takes power budget constraints into consideration.
   - Aims at minimizing the average splitting losses of the tree.
   - Balancing procedure:

![Diagram of Balanced Light-Tree (BLT)](image)
Several multicast routing algorithms are used for the simulations.

Multicast Routing Algorithms

- Cost
  - Minimum Steiner Tree (MST)
  - Optimized Shortest Paths Tree (OSPT)
- Power Budget Constraints
  - Balanced Light Tree (BLT)
- Physical Layer Impairments
  - Balanced Light Tree_Q (BLT_Q)
  - Balanced Light Tree_Q_tolerance (BLT_Q_tolerance)
Multicast Routing Algorithms

- **BLT_Q**: Aims at maximizing the average Q-value of the tree.
  - Balancing procedure:

- **BLT_Qtolerance**: improves on the BLT_Q by maximizing the Q-factor only at those destination nodes that the Q value below the Qtolerance value.
The balancing part of the algorithm terminates when two successive iterations fail to increase the minimum Q-factor.

Tends to create shallower trees increasing the Q-value at the destination nodes and increasing the total number of the links in the tree.

**BLT_{Q_{tolerance}}:**

- Aims at maximizing the average Q-value of the tree but keeping the total number of the links in the tree as low as possible.
- Considering that the tolerance Q-factor is k, this algorithm maximizes the Q-factor only at those destination nodes that the Q-factor is below k.
- Terminates if the Q-value of all destination nodes in the tree is above k, or if two successive iterations fail to increase the minimum Q-factor.
Simulation Parameters

(Network:

- 50 nodes, 196 bidirectional links, average node degree of 3.92, maximum node degree of 6, an average distance between the links of 60 Km.

Dynamic System:

- Poisson arrivals
- Exponentially distributed holding times with a unit mean.
- 100 Erlangs load.
- For each run 5,000 requests were generated for each multicast group size.
- The results for each simulation point were obtained as the average of 5 runs.

In the MC-RWA algorithm: Multicast request is accepted if
- A route and wavelength assignment can be found.
- The Q-factor for each path on the tree is above the predetermined Q threshold.
- There are available Txs and Rxs for that connection, Otherwise blocked.)
Simulation Parameters

• To determine the Q-value for each multicast call, a baseline system Q-value is first calculated based on the signal and noise terms, assuming:
  • 10 Gbps bit rate
  • a pre-amplified photodiode
  • 32 wavelengths in each fiber spaced at 100 GHz.
  • +5dBm power launched into the system.

• To include other common physical layer impairments a Q-budgeting approach is used that starts from the Q-value for the baseline system and budgets Q-penalties for the various physical layer impairments present.

• Each Q-penalty is calculated as the Q (in dB) without the impairment in place minus the Q (in dB) with the impairment present.
Impairment Aware - MC-RWA Algorithm

For each multicast connection request, the algorithm first solves the multicast routing problem and then assigns a wavelength for that tree (first-fit algorithm).

- **Blocked:** There is no available wavelength for the entire tree.
- **Accepted:**
  - A route and wavelength assignment can be found.
  - The Q-factor for each path on the tree is above the predetermined Q threshold.
  - There are available Txs and Rxs for that connection
- If the physical impairments constraints are not met, a new wavelength assignment is implemented and the heuristic is repeated until no new wavelength assignment is possible.
Simulation Results

- **BLT_Q_8.5** that takes the PLIs into account performs the best compared to the other multicast routing algorithms for both cases,
- **Pr. Blocking in tunable case** is increased compared to the fixed case, since in fixed Txs/Rxs case a larger number of Txs/Rxs is used.
Multicast Protection

- It is important that the multicast traffic is not only routed efficiently through the optical network but it is protected against any possible failures in the network.

- Fiber cuts occur often and are the predominant form of failure.

- A fiber cut (link failure) may jeopardize the entire multicast session
**Objective:** Ensure that every affected destination can receive the information from the source via the backup path(s) after the failure.

**Dedicated:** Resources along the backup path(s) are dedicated for only one connection and are not shared with the backup paths for other connections.

**Cross-Shared:** Resources along a backup path may be shared with other backup paths for other connections.
Multicast Protection-
Tree-based

Link-Disjoint:
1. A primary tree.
2. A link-disjoint backup tree.

Arc-Disjoint:
1. A directed primary tree.
2. A directed arc-disjoint backup tree

Redundant capacity reaches the 100 %.
Multicast Protection-Path-based

1. Find primary Light-tree.
2. Divides primary tree into several paths according to the destination nodes.
3. For each path a minimum cost path from the source to the destination node is computed, that is arc-disjoint from its primary path.

1. \{s – d_1\}
2. \{s – d_2\}
3. \{s – d_3\}

**Self-Sharing:** Backup paths can share the primary arcs on the primary tree, as long as there are path arc-disjoint.
Multicast Protection-
Segment-based

1. Find primary light-tree.
2. Divide primary light-tree to un-overlapped segments according to the segment points of the tree.
3. Find the backup paths for each segment.

- Definitions:
  - **Segment**: A path between two segment points.
  - **Segment points**: Splitting nodes, source and destination nodes.
Multicast routing and protection algorithms

- Each segment is protected by finding the minimum cost path between the segment points of each segment.
- The backup paths must be arc-disjoint from their primary segments.
Multicast Protection-
Segment-based

- Sister Node First Algorithm (SSNF)
  - Differs from the conventional SP in the way the segments are identified
  - **Definitions:**
    - **Sister Nodes:** Nodes with a common parent in the tree.
    - **Segment points** and **segments** are as previously defined.
  - The first segment is protected as in the conventional case.
  - The next segments are protected by computing the minimum cost trees that start from the splitting nodes of each segment and span the sister nodes in the sets.

\[ \{s \rightarrow m\} \]
\[ \{m \rightarrow n,d1\} \]
\[ \{n \rightarrow d3,d2\} \]
Multicast Protection-
Segment-based

- Level Protection Algorithm (LPA)
  - Differs from other segment based schemes in the way the segments are identified

- Divides the primary light-tree into un-overlapped segments based on the levels of the tree and finds backup paths for each Level segment.

- Definitions:
  - **Segment**: a path between two segmentation nodes in the tree.
  - **Segmentation node**: source node and destination nodes.
  - **Level(i) of a segmentation node**: the number of the segments between that segmentation node and the source.
  - **Level (i-1, i) segment**: is the set of all the segments of the tree that are between level (i-1) and level (i) segmentation nodes.
Multicast Protection-
Segment-based (LPA)

Segmentation nodes, levels and level segments are identified
Multicast Protection-Segment-based (LPA)

- **Backup path:** A minimum cost tree that starts from any segmentation node in lower levels, and spans every segmentation node in the current level.

- **Example:** if we want to protect the segmentation nodes in level 2, a minimum cost tree is computed that starts from any segmentation node in levels 0 or 1, and spans every segmentation node in level 2.

- **Constrain:** The backup tree, must be arc disjoint from its primary level segment and from every level segment that lies between higher levels.
Simulation Parameters

Network:
- 50 nodes
- 196 bidirectional links
- 64 wavelengths

Dynamic System:
- Poisson arrivals
- Exponentially distributed holding times with a unit mean.
- 100 Erlangs load.
- For each run 5,000 requests were generated for each multicast group size.
- The results for each simulation point were obtained as the average of 5 runs.

MC-RWA algorithm:
Accepted:
- A route and wavelength assignment can be found for both the primary and the backup trees,
  - The Q-factor for each path on both trees is above the predetermined Q threshold.
  - There are available Txs and Rxs for that connection.
Simulation Results

- **Assumptions**: Fixed Txs/Rxs, Q threshold = 8.5 dBQ
- **LPA** performs the best in both cases compared to the other segment based protection algorithms.
- **Cross-Sharing** significantly improves the network performance.
Conclusions and Future Work

Conclusions:
• Different node architectures and engineering designs produce different multicast group blocking, a strong indicator that a better interaction between physical and logical layers is needed for multicast connection provisioning.

Future Work:
• Our current work focuses on further accounting and determining the impact of PDG and PDL on the algorithms and the system performance.
• Future work focuses to the provisioning and protection of groupcast requests when PLIs are taken into account.
• Additional work has been done on unicast connections taking into account the PLIs.
• Additional work has been done on grooming substrate connections for multicast applications (grooming for groupcast applications is scheduled as future work).