Resource Allocation for Space-Division Multiplexing: Optical White Box Versus Optical Black Box Networking

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Common Optical Node Architecture

- Amplifiers (EDFA, etc)
- Compensation Amplifiers
- ROADM (CDC for extra flexibility)
- IN 1
- IN 2
- IN 3
- OUT 1
- OUT 2
- OUT 3
- Add
- Drop

UCDAVIS
Optical Black Box Vs. Optical White Box

ROADM (Black Box)
Internal connections are hardwired.

Architecture on Demand Switch (White Box)
Dynamically reconfigurable backplane

MUX: Multiplexer  DEMUX: Demultiplexer  SSS: Spectrum Selective Switch
EDFA: Erbium Doped Fibre Amplifier  PLZT: (Pb, La)(Zr, Ti)O3

Obs: 96x96 3D-MEMS is only 20% more expensive than 1x16 Spectrum Selective Switch (SSS)
Elastic Space Division Multiplexing (SDM) Networks

• Multi-Mode Fiber (MMF): different propagation modes
• **Multi-Core Fiber (MCF): different cores, each carrying a signal**
• Few-Mode Fiber (FMF): similar to MMF, but fewer
• Few-Mode Multi-Core Fiber (FM-MCF): FMF and MCF
• Single-Mode Fiber (SMF) Bundles: common long distance systems

• Spatial-spectral superchannels
Contribution and Considerations

- Investigate planning and dimensioning of MCF-based elastic SDM networks considering quasi-static traffic model. Propose an algorithm to solve the Routing, Modulation, Spectrum, and Core Allocation (RMSCA) problem in these networks considering Cross-Talk (XT).
- Compares optical white boxes (AoDs) and black boxes (ROADMs).
- Bandwidth Variable Transceivers (BVTs), weakly-coupled MCFs, no MIMO (it would require different signals to not be decoupled).
- BPSK, QPSK, 8...64-QAM and PDM.
- ROADM are Colorless, Directionless, and Contentionless.
Cross-Talk (XT) and Multi-Core Fibers (MCF)

\[ XT = \frac{n - n \cdot \exp\left(-\left(n + 1\right) \cdot 2\frac{\kappa^2}{\beta} \frac{R}{\Lambda} L\right)}{1 + n \cdot \exp\left(-\left(n + 1\right) \cdot 2\frac{\kappa^2}{\beta} \frac{R}{\Lambda} L\right)} \]

*N is the number of adjacent cores.

Provisioning Algorithm

Phase 1
- Compute the feasible modulation format for each path and then the spectrum requirement for each capacity demand

Phase 2
- Sort demands in descending form according to the ordering function value

Phase 3
- Select the route, spectrum resources, and core that satisfy the crosstalk threshold and optimize the objective function

Ordering function value = spectrum \times \text{path length for first-shortest path}

The RMSCA solution for the maximum possible number of demands
ROADM Ordering Function

• To reduce number of SSSs, focus on using already lit cores

Cost = (# New link cores lit) * (XT value for path)

Fig. 9. ROADM for MCF-based SDM networks.
AoD Ordering Function

- AoD: reconfigure to remove unnecessary switch modules, and (more importantly) optical backplane can route input to output without SSS. Thus, spread demands through fiber to take advantage of that.

Cost = (# Additional switching modules) * (XT value for path)
Allocation Decision

• Two types:
  • Modulation Format Fixed (MFF) – if demand cannot be provisioned within XT threshold, it is dropped
  • Modulation Format Switching (MFS) – if demand cannot be provisioned within XT threshold, downgrades modulation level from the most spectral efficient to some lower modulation that passes the XT threshold test
Results – Overview

- BT Topology: 22 nodes, 70 unidirectional links
- Demands: uniform sd-pairs and bandwidths (from 10 to 500Gbps)
- Utilization increases by 30% every epoch besides new demands
- Confidence Level of 95%, Conf. Interv. < 5%
Results – Part 1

- Incorporating XT values while computing through cross-layer optimization helps (specially AoD)
- ROADM first seek spectrum resources on non-adjacent cores of network links, exploiting their dense intra-node connectivity. Once these are used up, allocated resources are reconfigured to demands to minimize the level of XT
- AoD occupies (spreading) resources on different link cores to maximize the fiber switching. Though disjoint spectrum slots are sought, chances of spectrum overlapping are still higher compared to ROADM
- MFS-AoD better than MFF-AoD for low traffic, but similar for higher traffic because modulation is lowered due to XT (widening bands)
- Prioritizing the cost function to minimize deployment of new switching modules (MFS-AoD (dif.)) hurts successful traffic
Results – Part 2

• Performance of MFS-ROADM approximately the same as benchmark. Both use same criteria: to use up spectrum resources of a core before lighting other cores (lit cores proportional to # of SSSs)
• AoD-based up to 60% less SSSs: achieved by enhancing fiber switching and relocating the prior installed modules
• For single-core (SC) amplifiers,
  • ROADM net: requires sum of inline plus the ones for compensating amplifiers
  • AoD net: fiber switching raises # of inline amplifiers considerably, compared to ROADM in low traffic. For high traffic, ROADM needs more (compensating amps) since most of the fiber cores are lit
• For Multi-core (MC) amplifiers, # of inline amplifiers becomes independent of the lit cores, enabling AoD nets to use less amplifiers
Results – Part 3

- AoD-based network, in general, and MFF-AoD, in particular, have higher levels of XT (smaller value of dB) with respect to the ROADM scenario.
- Modulation switching to lower levels enables MFS-AoD to alleviate the XT compared to AoD-MFF.
- MFS-ROADM utilizes resources on non-adjacent cores of the fiber to minimize the impact of XT.
- MFS-AoD use partial resources on all cores (with minimum spectrum overlapping among neighbor cores) to maximize fiber switching.
Results – Part 4

- For MFS-AoD, switching resources (and thus intra-nodal connectivity) grow with the increase in traffic volume. More intra-connected nodes improve chances of finding spectrum resources on shorter paths. Thus, the path length for MFS-AoD drops with the rise in network traffic.
- For MFS-ROADM, path length goes up with the increase in network traffic volume. Because the cost function forces the selection of shorter paths (to achieve low XT) when network spectrum resources are partly occupied. As traffic increases, the candidate solution space shrinks, leading to the selection of longer paths.
- Modulation level (for MFS strategy) not only depends on the path length but also on the XT. The ratio of provisioned traffic for MFS-ROADM is higher than for MFS-AoD, which indicates more likelihood of signal interference on longer routes for MFS-ROADM. Thus, the signal robustness to XT is enhanced by employing a relatively lower level of modulation compared to MFS-AoD.
Extra Slides
Algorithm Pseudo-Code

<table>
<thead>
<tr>
<th>Algorithm 1 XT Aware RMSCA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1:</strong> ( \mathcal{G}(V, E) ): network topology;</td>
</tr>
<tr>
<td><strong>2:</strong> ( \mathcal{C} ): set cores;</td>
</tr>
<tr>
<td><strong>3:</strong> ( S ): set available spectrum slots;</td>
</tr>
<tr>
<td><strong>4:</strong> ( D ): set demands sorted for ordering function;</td>
</tr>
<tr>
<td><strong>5:</strong> ( P ): path matrix; ( \pi^d \in \mathcal{P} ) set candidate paths for ( d \in D );</td>
</tr>
<tr>
<td><strong>6:</strong> ( M ): set modulation levels; ( m_{\pi^d} \in M ) highest attainable level for ( d ) on path ( \pi^d \in \pi^d );</td>
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<tr>
<td><strong>7:</strong> ( \mathcal{N}_k ): set link core combinations for path ( \pi^d );</td>
</tr>
<tr>
<td><strong>8:</strong> ( \Omega ): set computed spectrum slots; ( \omega_{\pi^d} \in \Omega ) slots needed for ( d ) on path ( \pi^d ) using modulation level ( m_{\pi^d} );</td>
</tr>
<tr>
<td><strong>9:</strong> ( \mathcal{X} \mathcal{T} ): set crosstalk thresholds; ( x_{l_m} \in \mathcal{X} \mathcal{T} ) crosstalk threshold for modulation format ( m );</td>
</tr>
<tr>
<td><strong>10:</strong> Initialization: ( \tilde{C} = -1 );</td>
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<tr>
<td><strong>11:</strong> for each demand ( d \in D ) do</td>
</tr>
<tr>
<td><strong>12:</strong> Initialization: ( \tilde{M} =</td>
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<tr>
<td><strong>13:</strong> Initialization: ( \tilde{S} = 0 );</td>
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<tr>
<td><strong>14:</strong> for each path ( \pi^d \in \pi^d ) do</td>
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<td><strong>15:</strong> for each ( l_{\pi^d} \in \mathcal{N}_{\pi^d} ) do</td>
</tr>
<tr>
<td><strong>16:</strong> Let ( \Lambda_{l_{\pi^d}} ) be set of free contiguous slots for ( l_{\pi^d} );</td>
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<tr>
<td><strong>17:</strong> if ( \omega_{\pi^d} \leq \Lambda_{l_{\pi^d}} ) then</td>
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<tr>
<td><strong>18:</strong> Increment ( \tilde{S} ) by 1;</td>
</tr>
<tr>
<td><strong>19:</strong> Compute ( x_t ) for ( d ) and those prior</td>
</tr>
<tr>
<td>established superchannels that are inflicted by ( \Lambda_{l_{\pi^d}} );</td>
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<tr>
<td><strong>20:</strong> if ( x_t \leq x_{t_m} ) for ( d ) and all the affected superchannels then</td>
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<tr>
<td><strong>21:</strong> Compute cost function ( C_{l_{\pi^d}, l_{c_{\pi^d}}, \Lambda_{l_{\pi^d}}} );</td>
</tr>
<tr>
<td><strong>22:</strong> end if</td>
</tr>
<tr>
<td><strong>23:</strong> end if</td>
</tr>
<tr>
<td><strong>24:</strong> end for</td>
</tr>
<tr>
<td><strong>25:</strong> end for</td>
</tr>
<tr>
<td><strong>26:</strong> if ( \tilde{S} \neq 0 ) then</td>
</tr>
<tr>
<td><strong>27:</strong> Try subroutine _xxx;</td>
</tr>
<tr>
<td><strong>28:</strong> else</td>
</tr>
<tr>
<td><strong>29:</strong> Reject ( d );</td>
</tr>
<tr>
<td><strong>30:</strong> end if</td>
</tr>
<tr>
<td><strong>31:</strong> end for</td>
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</tbody>
</table>

**Try subroutine \_MFF**

Select \( \hat{\pi}^d \), \( l_{\pi^d} \), and \( \Lambda_{l_{\pi^d}} \) with \( \tilde{C} = \min \{ C_{l_{\pi^d}, l_{c_{\pi^d}}, \Lambda_{l_{\pi^d}}} \} \); |

if \( \tilde{C} \neq -1 \) then Return \( \hat{\pi}^d \), \( m_{\pi^d} \), \( l_{\pi^d} \), and \( \Lambda_{l_{\pi^d}} \); |

else Reject \( d \); end if

**Try subroutine \_MFS**

Select \( \hat{\pi}^d \), \( l_{\pi^d} \), and \( \Lambda_{l_{\pi^d}} \) with \( \tilde{C} = \min \{ C_{l_{\pi^d}, l_{c_{\pi^d}}, \Lambda_{l_{\pi^d}}} \} \); |

if \( \tilde{C} \neq -1 \) then Return \( \hat{\pi}^d \), \( m_{\pi^d} \), \( l_{\pi^d} \), and \( \Lambda_{l_{\pi^d}} \); |

else Decrement \( \tilde{M} \) by 1; Downgrade the modulation for \( d \) by one level and compute new values for \( \Omega \); |

if \( \tilde{M} \neq 0 \) then Repeat Steps 13–23; |

else Reject \( d \); end if

end if