Assessment of Flex-Grid/MCF Optical Networks with ROADM Limited Core Switching Capability

R. Rumipamba-Zambrano¹, F-J. Moreno-Muro², P. Pavón-Marino², J. Perelló¹, S. Spadaro¹, and J. Solé-Pareta¹

¹Advanced Broadband Communications Center (CCABA), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain
²Telecommunication Networks Engineering Group (GIRTEL), Universidad Politécnica de Cartagena (UPCT), Cartagena, Spain
Outline

- Motivation
- Transmission Reach Estimation in MCF-enabled Networks
- Proposed ROADM Architecture
- Case Study and Results
- Final Remarks
Motivation

- **Flex-Grid** takes advantage of flexibility at the transceiver, while ensuring efficient utilization of the optical spectrum.

- **Space Division Multiplexing (SDM)** is the prime candidate to overcome the nonlinear Shannon’s fundamental limit of single-mode fiber capacity.

- Weakly-coupled Multi-core fibers (**MCFs**) are an attractive SDM fiber candidate given their extremely low Inter-core Crosstalk (**ICXT**).

<table>
<thead>
<tr>
<th>MCF</th>
<th>Worst ICXT [dB/Km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 [1]</td>
<td>-84.7</td>
</tr>
<tr>
<td>12 [2]</td>
<td>-61.9</td>
</tr>
<tr>
<td>19 [3]</td>
<td>-54.8</td>
</tr>
</tbody>
</table>

Motivation (1/4)

- SDM Reconfigurable Optical Add/Drop Multiplexers (ROADM) design is a challenge taking into account several degrees of freedom.

- Having full interconnection at ROADMs between input ports and output ports is very expensive, and even more with new space dimension $\rightarrow$ fully non-blocking architecture (FNB-ROADM architecture).
  - FNB architecture assumes that signals can be freely switched from any input fiber (& core) to any output fiber (&core).
Motivation (2/4)

- **Joint-switching (JoS) [4]** relaxes the hardware requirements of the ROADM and it is mandatory for strongly-coupled SDM fibers (some MCFs, FMFs, FM-MCFs...). **Spatial super-channel allocation (Spa-SCh)** policy is mandatory.

- **Architecture on Demand (AoD) [5]** shares the hardware modules on demand via node programmability. It assumes core switching capabilities → **Different super-channel allocation policies (Spe-SCh, Spa-SCh, S2-SCh).**


Motivation (3/4)

- In this work, we propose an alternative architecture to reduce the node complexity and cost:
  - Limit the core switching capabilities at the intermediate nodes: forcing the *core continuity constraint* (CCC-ROADM architecture)
TR Estimation

- TR depends on many different variables like the type of fiber, the amplification scheme, the dispersion map, the nonlinear effects compensation capability...

- TR in MCFs is limited by Signal-To-Noise Ratio (SNR) and ICXT.
  - SNR: We consider the Gaussian-Noise (GN) model and with parameters according to “Link 1”. [6]
  - ICXT: We consider the worst-aggregate ICXT among cores.

### Overall Transmission Reach [km]

<table>
<thead>
<tr>
<th>C</th>
<th>BPSK</th>
<th>QPSK</th>
<th>16–QAM</th>
<th>64–QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>&gt;20000</td>
<td>9000</td>
<td>2000</td>
<td>600</td>
</tr>
<tr>
<td>12</td>
<td>&gt;20000</td>
<td>9000</td>
<td>2000</td>
<td>600</td>
</tr>
<tr>
<td>19</td>
<td>4755</td>
<td>2383</td>
<td>599</td>
<td>150</td>
</tr>
</tbody>
</table>

Proposed Architecture (1/4)

(B&S) FNB-ROADM Architecture:

- The number of splitters and SSSs is $FxC$ and grows linearly with the number of cores.
- The number of input ports of each SSS is $FxC$ and grows linearly with the number of cores.
- The attenuation caused by the splitters is approximately $10 \log(FxC)$, thus growing logarithmically with the number of cores.

F: node degree
C: core count
Proposed Architecture (2/4)

(B&S) CCC-ROADM Architecture:

- The number of splitters and SSSs is $FxC$ and grows linearly with the number of cores.
- The number of input ports of each SSS is now $F$ instead of $FxC$, and does not grow with the number of cores.
- The attenuation (in dB) caused by the splitters is approximately $10 \log (F)$ instead of $10 \log (FxC)$, and does not grow with the number of cores.

$F$: node degree
$C$: core count
Proposed Architecture (3/4)

### CCC-ROADM vs. FNB-ROADM Architecture

Splitter Atenuation in [dB] (CCC, FNB)

<table>
<thead>
<tr>
<th>C</th>
<th>F = 2</th>
<th>F = 4</th>
<th>F = 8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CCC</td>
<td>FNB</td>
<td>CCC</td>
</tr>
<tr>
<td>7</td>
<td>3.01</td>
<td>11.46</td>
<td>6.02</td>
</tr>
<tr>
<td>12</td>
<td>3.01</td>
<td>13.80</td>
<td>6.02</td>
</tr>
<tr>
<td>19</td>
<td>3.01</td>
<td>15.80</td>
<td>6.02</td>
</tr>
</tbody>
</table>

Number of Required Input Ports per SSS (CCC, FNB)

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<tr>
<td></td>
<td>CCC</td>
<td>FNB</td>
<td>CCC</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>24</td>
<td>4</td>
</tr>
<tr>
<td>19</td>
<td>2</td>
<td>38</td>
<td>4</td>
</tr>
</tbody>
</table>

### Proposed Architecture (4/4)

**Decision Variable:**

- \(x_{ps}, p \in \mathcal{P}, s \in \mathcal{S}\): binary decision variable; 1 if path \(p\) has a first slot \(s\) (the \(s(t(p))\) slots occupied are contiguous); 0 otherwise.
- \(x_{pcs}, p \in \mathcal{P}, c \in \mathcal{C}, s \in \mathcal{S}\): binary decision variable; 1 if path \(p\) uses the core index \(c\) and it has a first slot \(s\) (the \(s(t(p))\) slots occupied are contiguous); 0 otherwise.

<table>
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<tr>
<th>FNB–ROADM ILP Model</th>
<th>CCC–ROADM ILP Model</th>
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</table>
| \[
\text{min } \sum_{p \in \mathcal{P}, s \in \mathcal{S}} s_p l(p) x_{ps} \\
\text{subject to:} \\
\sum_{p \in \mathcal{P}_d, c \in \mathcal{C}, s \in \mathcal{S}} r_p x_{ps} \geq h_d \quad \forall d \in \mathcal{D} \\
\sum_{p \in \mathcal{P}_e} x_{ps} \leq C \quad \forall e \in \mathcal{E}, s \in \mathcal{S}
\] | \[
\text{min } \sum_{p \in \mathcal{P}, c \in \mathcal{C}, s \in \mathcal{S}} s_p l(p) x_{pcs} \\
\text{subject to:} \\
\sum_{p \in \mathcal{P}_d, c \in \mathcal{C}, s \in \mathcal{S}} r_p x_{pcs} \geq h_d \quad \forall d \in \mathcal{D} \\
\sum_{p \in \mathcal{P}_e} x_{pcs} \leq 1 \quad \forall e \in \mathcal{E}, c \in \mathcal{C}, s \in \mathcal{S}
\] |
Case Study and Results

- We evaluate CCC-ROADM architecture implementing the ILPs formulations in Net2Plan tool and JOM library (CPLEX interface)

- Best sigle-mode (homogeneous) MCF prototypes are assessed:

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- 4THz C-Band, $\Delta f_s = 12.5$ GHz, 120 FSs/core

- GB = 10 GHz, flex. baud-rate, different modulation formats: PM-BPSK, PM-QPSK, PM-16QAM, PM-64QAM.

- Different transponders at line-rates $R=\{40, 100, 400\}$ Gb/s
Case Study and Results (1/2)

Final Remarks (1/2)

- The SDM ROADM architectures can be greatly simplified forcing the CCC with minimal impact on the network throughput
  - Reduce the SSS size and the attenuation caused by the splitters in a B&S scheme
  - Impact inexistent for $C=7$, around 1% for $C=12$ and between 10% and 5% for $C=19$ (in T7S and I2 networks, respectively)

- The best single-mode MCF prototypes, like the 7-core and 12-core MCF has a good relation throughput/$(C*|E|)$ (as a metric of techno-economic efficiency)

<table>
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<tr>
<th>Topology</th>
<th>$C = 7$</th>
<th>$C = 12$</th>
<th>$C = 19$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T7S</td>
<td>3.3</td>
<td>3.3</td>
<td>1.5</td>
</tr>
<tr>
<td>I2</td>
<td>1.5</td>
<td>1.5</td>
<td>0.8</td>
</tr>
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- The 19-core MCF may compromise its feasibility unless a TR compensation mechanism is deployed

THANK YOU
QUESTIONS?

Contact Info:
Rubén Rumipamba (rrumipam@ac.upc.edu)