Selection of Spectral-Spatial Channels in SDM Flexgrid Optical Networks

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Agenda

• Introduction and Motivation
• Optimization Problem
• Algorithm
• Results
• Conclusions
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• **Introduction and Motivation**
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Internet Capacity Crunch – Why???

• **Bandwidth-hungry applications/services:**
  – HDTV, video streaming, 4K
  – Big data processing
  – Game streaming

• **Increasing number of users/devices:**
  – Internet reaches almost every person on Earth
  – Every user uses many devices (smartphone, iPad, PC, TV, etc)
  – Internet of Things (IoT) - the number of devices connected to the Internet will grow from 5 billion now up to 50 billion in 2020

• **Evolution access network technologies:**
  – FTTx
  – LTE 300 Mbps
  – 5G 10Gbps

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Cisco Traffic Forecasts

- The **Cisco Global Cloud Index (GCI)** forecasts data center and cloud traffic and related trends
- The **Cisco Visual Networking Index (VNI)** is the company's ongoing effort to forecast and analyze the growth and use of IP networks worldwide
- **CAGR** (Compound Annual Growth Rate)
Predicted CAGR

IP Traffic
• 2013 VNI report for years 2012-2017 report, CAGR=23%
• 2014 VNI report for years 2013-2018 report, CAGR=21%
• 2015 VNI report for years 2014-2019 report, CAGR=23%
• 2016 VNI report for years 2015-2020 report, CAGR=22%

Content Delivery Network (CDN) Traffic
• 2013 VNI report for years 2012-2017 report, CAGR=34%
• 2014 VNI report for years 2013-2018 report, CAGR=34%
• 2015 VNI report for years 2014-2019 report, CAGR=38%
• 2016 VNI report for years 2015-2020 report, CAGR=34%
CAGR 23%

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How to overcome the capacity crunch???

- Deliver network traffic in a smart way (CDN, anycasting, multicasting, etc.)
- Limit network traffic (blocking P2P traffic, throttling video traffic, etc.)
- **Update backbone (optical) networks**
Evolution of Optical Networks

• **Currently**, most of the transport optical networks use WDM (Wavelength Division Multiplexing) technology with fixed-grid

• Possible ways to increase capacity of optical networks:
  
  – **Elastic Optical Networks (EONs)** with higher flexibility in the spectrum domain (flex-grid)
  
  – **Space-Division Multiplexing (SDM)** with higher flexibility in the space domain

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The key idea behind SDM is to use the **space domain**, in which the spatial resources can be flexibly assigned to different traffic demands.

- SDM allows to **increase** the overall **transmission capacity in a cost-effective** manner by **integrating** to a certain extent multiple transmission systems in parallel.
SDM Technologies

- **Fiber bundle** – standard fibers, often deployed in bundles (to offset the costs of digging trenches)

- **Multicore fiber** – fibers with multiple cores within a single fiber cladding, forming multicore fibers (MCFs), offer an increase in available bandwidth equal to their core count

- **Multimode fiber** – fibers with a single, large core, which can carry additional optically-guided spatial modes, few-mode fibers (FMFs) offer a potential capacity multiplier equal to the mode count
SDM Scenarios

[Spectral dimension/spatial dimension]

• **Flexgrid/Single** – parallel transmission in EON network

• **Flexgrid/Fixed** – SSChs can be transmitted using different SpRcs, however, within the same spectrum segment

• **Flexgrid/Flexible** – full spectral and spatial flexibility in forming SSChs is allowed. Although this scenario enables best resource utilization, it may lead to fragmentation of spectrum

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Independent switching of spatial mode and wavelength channel (i.e., space–wavelength granularity)
Wavelength switching across all spatial modes (wavelength granularity), also called spectral switching or joint switching.
**Independent switching** or **wavelength switching** across spatial mode subgroups (fractional space– full wavelength granularity), sometimes called **fractional joint switching** or **grouped spectral switching**
Pros and Cons of SDM

😊 Increase the overall transmission capacity of optical networks beyond the limits of WDM and EON networks in a cost-effective manner by integrating the SDM equipment (transceivers, switching devices) to enable to a certain extent realizing multiple transmission systems in parallel

😊 All advances of EONs can be used in SDM networks

😊 New fibers are required for multi-core or multi-mode transmissions

😊 Key network components for SDM (amplifiers, multiplexers, transceivers) are under development

😊 Crosstalks between cores/modes can limit transmission range

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Goal and Novelty

• The main goals of this work are:
  – To develop an effective heuristic algorithm for the Flexible scenario
  – To examine main characteristics of the Flexible scenario in terms of the spectrum usage
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Routing and Spectrum Allocation (RSA)

The basic optimization problem in EONs is RSA (Routing and Spectrum Allocation) that consists in selection for every demand of a routing path and spectrum with the following constraints:

• **Continuity constraint** states that in an absence of spectrum converters, the demand must use exactly the **same spectrum slots (optical corridor)** in all links included in the routing path.

• **Contiguity constraint** requires that slices assigned to a particular demand must be **adjacent (contiguous)**
Distance-Adaptive Transmission

• In SDM networks based on the concept of EONs, it is possible to use **various modulation formats**, e.g., BPSK, QPSK, 8-QAM, 16-QAM

• These modulation formats provide some **trade-off between spectrum efficiency and transmission range**, i.e., more spectrum effective modulation formats provide shorter transmission range

• A reasonable approach is a **distance-adaptive transmission (DAT)**, i.e., a modulation format for a particular demand is preselected based only on the transmission distance
# Distance-Adaptive Modulation Formats for Bit-Rate 400 Gb/s

<table>
<thead>
<tr>
<th></th>
<th>BPSK</th>
<th>QPSK</th>
<th>8-QAM</th>
<th>16-QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>#transceivers</td>
<td>8</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>#slices</td>
<td>25</td>
<td>13</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Range [km]</td>
<td>6300</td>
<td>3500</td>
<td>1200</td>
<td>600</td>
</tr>
</tbody>
</table>

Path length 900 km -> 8-QAM, 3 transceivers, 10 slices

Path length 1800 km -> QPSK, 4 transceivers, 13 slices
Demand Provisioning in SDM

- Demand on the selected path is assigned to a *spectral-spatial channel (SSCh)* using spectral resources that can be allocated on more than one SpRc
- In consequence, the **number of possible** (SSChs) in SDM networks is much **larger** comparing channels in EONs
- The basic optimization problem in SDM networks is **RSSA** (*Routing, Space and Spectrum Allocation*)

SDM – Example (1)

- Demand bit-rate is **1 Tbps**
- Path length is **3000 km**
- According to DAT, the selected MF is **QPSK**
- Since QPSK supports 100 Gbps per one transceiver, we need **10** transceivers (\(=1 \text{Tbps}/100 \text{Gbps}\)) and **30** slices of 12.5 GHz
30 slices required to establish 1 Tbps demand using QPSK on 3000 km path

SSCh on 1 SpRcs
31 = 30 + 1

SSCh on 3 SpRcs
39 = 30 + 6 + 3

SSCh on 6 SpRcs
42 = 30 + 6 + 6
ILP Model

objective
\[
\min \sum_{s \in S} y_s
\]

constraints
\[
\sum_{p \in P(d)} \sum_{c \in C(d,p)} x_{dpc} = 1 \\
\sum_{d \in D} \sum_{p \in P(d)} \sum_{c \in C(d,p)} \gamma_{dpcs} \delta_{edp} x_{dpc} \leq y_{esk} \\
\sum_{k \in K(e)} y_{esk} \leq |K(e)| y_{es} \\
\sum_{e \in E} y_{es} \leq |E| y_s
\]
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Greedy Algorithm

Require: set of demands $D$, sets $P(d)$ with candidate paths for each demand, SSCh comparing strategy $\textit{comp}$, sorting type $\textit{sort}$

1 function $\text{Greedy}(D, P, \textit{comp}, \textit{sort})$
2 $D := \text{sortDemands}(D, \textit{sort})$
3 for $i := 0$ to $|D|$ do
4 $d := D[i]$
5 $[p, ssch] := \text{FPCSpectrum}(P(d); \textit{comp})$
6 allocate($p$, $ssch$)
Tuning - Sorting

As sort, we consider one of the following metrics:

- **Slices** – the required number of slices on the shortest path
- **Distance** – the length (in km) of the demand’s shortest path
- **Hop count** – the number of links on the shortest path
Tuning – SSCh Selection

- Lowest Start (LS) — the SSCh of the lowest starting slice
- Lowest End (LE) — the SSCh of the lowest ending slice index is selected
- Penalty (PEN) — the SSCh with the lowest penalty $\Theta_1(c)$ is selected:
  $$\Theta_1(c) = \alpha \cdot (guardband(c) + \text{rounding}(c)) + \text{end}(c)$$
- Demands-Varying Penalty (DVP) — the SSCh with the lowest penalty $\Theta_2(c)$ is selected:
  $$\Theta_2(c) = \alpha \cdot (1 - \tau) \cdot (guardband(c) + \text{rounding}(c)) + (1 - \alpha) \cdot \tau \cdot \text{end}(c)$$

- $\text{end}(\text{SSCh})$ returns an index of the highest slice used by SSCh
- $\text{rounding}(\text{SSCh})$ returns the amount of slices wasted for rounding
- $\text{guardband}(\text{SSCh})$ returns the amount of slices used for guardbands
- $\tau$ is equal to the ratio of currently allocated demands to all demands
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Assumptions

• Transceivers operate at fixed baud rate of 28 GBaud and each transceiver transmits/receives an optical channel (optical carrier) that occupies 3 slices of 12.5 GHz

• A fixed guardband defined as 1 slice of 12.5 GHz

• Four modulation formats: BPSK, QPSK, 8-QAM, and 16-QAM with range 6300 km, 3500 km, 1200 km and 600 km, with bit-rate: 50 Gbps, 100 Gbps, 150 Gbps and 200 Gbps, respectively

• Each demand has the bit-rate selected at random from range 50 Gbps to 1 Tbps with 50 Gbps granularity

• Number of candidate paths for each demand is 30
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## Tuning – Number of Slices

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Slice</th>
<th>Distance</th>
<th>Hop Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS</td>
<td>1066.1</td>
<td>1125.8</td>
<td>1079.5</td>
</tr>
<tr>
<td>LE</td>
<td>1300.8</td>
<td>1367.3</td>
<td>1331.3</td>
</tr>
<tr>
<td>PEN(α=0.2)</td>
<td>1300.1</td>
<td>1366.7</td>
<td>1335.5</td>
</tr>
<tr>
<td>PEN(α=0.5)</td>
<td>1301.4</td>
<td>1365.3</td>
<td>1332.6</td>
</tr>
<tr>
<td>PEN(α=0.8)</td>
<td>1264.1</td>
<td>1323</td>
<td>1288.1</td>
</tr>
<tr>
<td>DVP(α=0.2)</td>
<td>1236.7</td>
<td>1319</td>
<td>1278.6</td>
</tr>
<tr>
<td>DVP(α=0.5)</td>
<td>1202.3</td>
<td>1274.1</td>
<td>1230.6</td>
</tr>
<tr>
<td>DVP(α=0.8)</td>
<td>1159</td>
<td>1217.5</td>
<td>1157.7</td>
</tr>
</tbody>
</table>
# CPLEX vs. Heuristic for Euro28

| $|P(d)|$ | $|D|$ | Number of slices | Execution time |
|-----|-----|-----|----------------|---------------|
|     |     | CPLEX | Greedy | CPLEX | Greedy |
| 4   | 20  | 28    | 28     | 260s   | <1ms   |
| 4   | 30  | 31    | 31     | 1h     | <1ms   |
| 4   | 40  | 34    | 34     | 1h     | <1ms   |
| 4   | 50  | Out of Memory | 58 | - | <1ms |
| 2   | 20  | 28    | 28     | 60s    | <1ms   |
| 2   | 30  | 25    | 31     | 1h     | <1ms   |
| 2   | 40  | 34    | 34     | 1h     | <1ms   |
| 2   | 50  | Out of Memory | 58 | - | <1ms |

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Spectrum usage for various types of demands – network Euro28 and 1 Pbps traffic

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Spectrum usage for various types of demands – network DT14 and 1 Pbps traffic

![Bar chart showing spectrum usage for different demands]
Spectrum usage for various types of demands – network Euro28 and 1 Pbps traffic

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Spectrum usage for various types of demands – network DT14 and 1 Pbps traffic

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Average execution time of the heuristic (in seconds) as a function of the number of SpRcs for, 1 Pbps traffic

<table>
<thead>
<tr>
<th>Network</th>
<th>Number of spatial resources</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Euro28</td>
<td>2</td>
</tr>
<tr>
<td>DT14</td>
<td>1</td>
</tr>
</tbody>
</table>
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Conclusions

- A greedy algorithm with different strategies for sorting of demands and allocation of spectral-spatial channels provides results close to optimal ones.
- Spectrum usage in examined topologies decrease almost proportionally with the increase of SpRcs.
- The Flexible scenario yields similar results the Single scenario. Flexible, despite its capability to form SSChs in both domains, most of the time selects SSChs which use only one SpRc.
- The Flexible scenario is very complex in terms of SSChs number, what results in high execution time of simple heuristic.
- Future work includes development of heuristic and metaheuristic methods that enable solving large problem instances.

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Thank you for attention

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