Wrocław University of Science and Technology

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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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

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

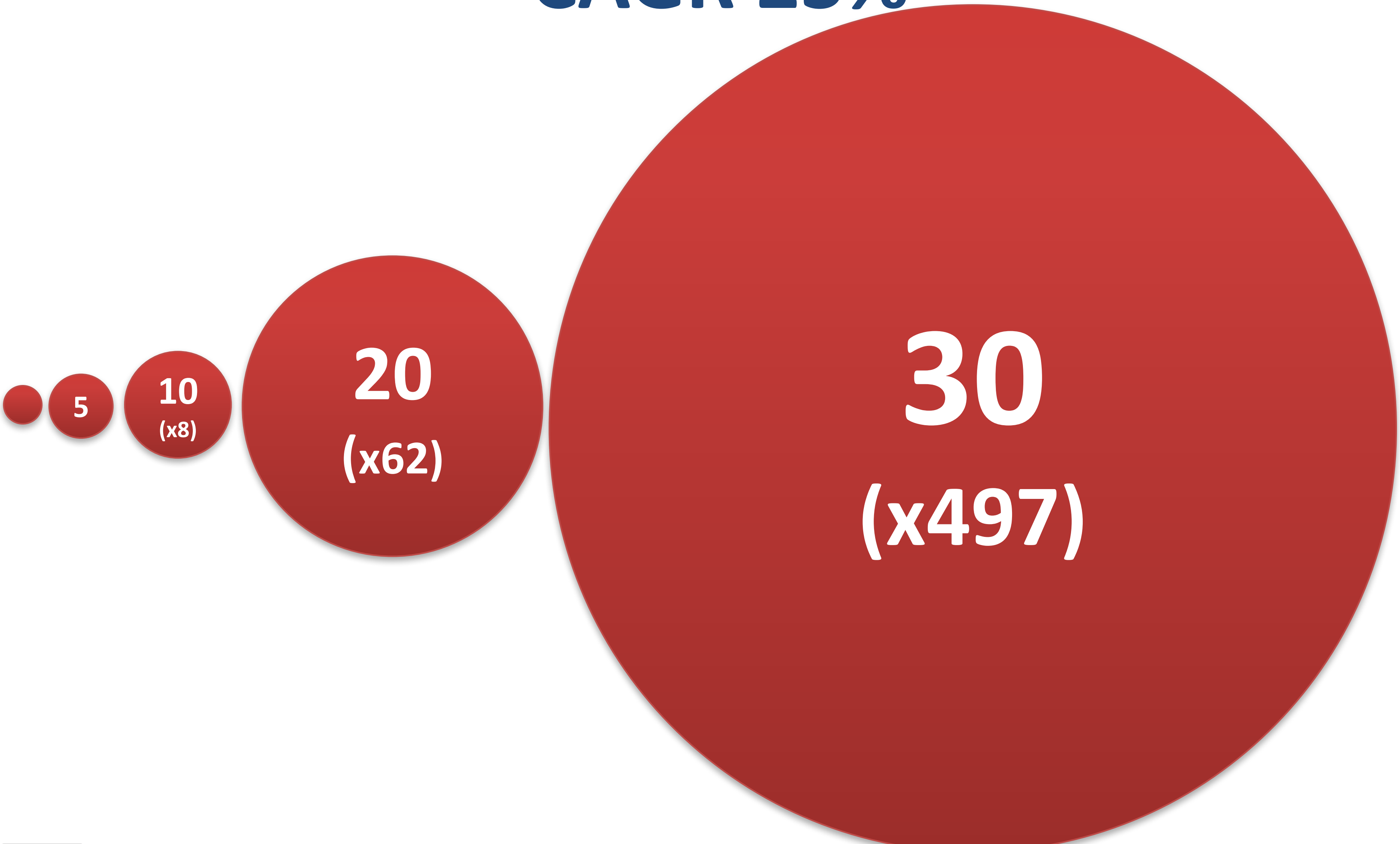
IP Traffic

- 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%**

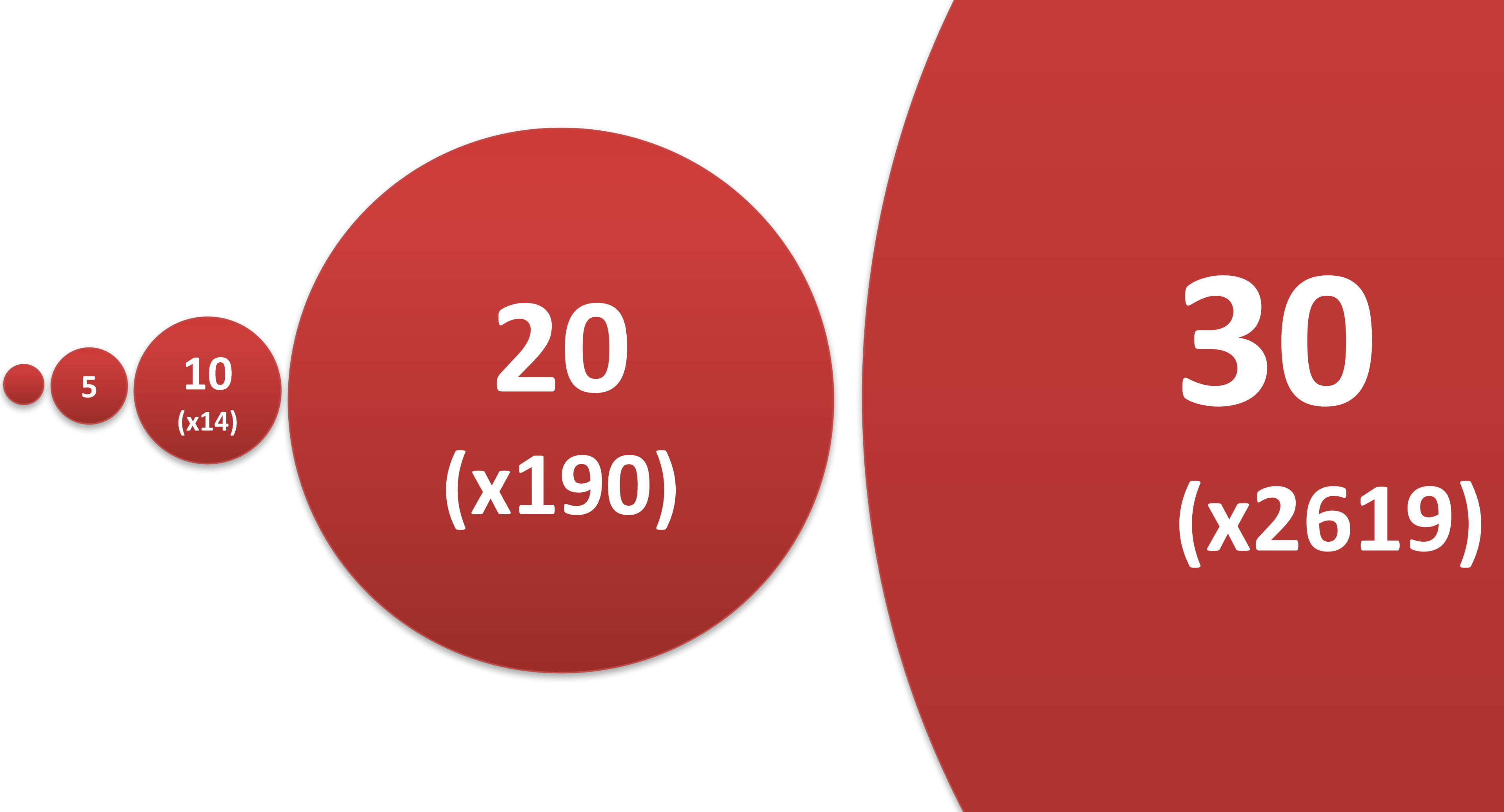
Content Delivery Network (CDN) Traffic

- 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%



CAGR 30%



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**

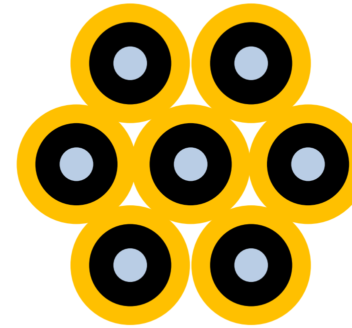
Evolution of Optical Networks

- **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

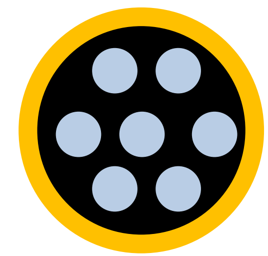
SDM

- 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

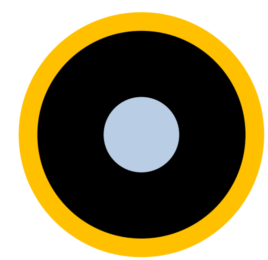
SDM Technologies



- **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



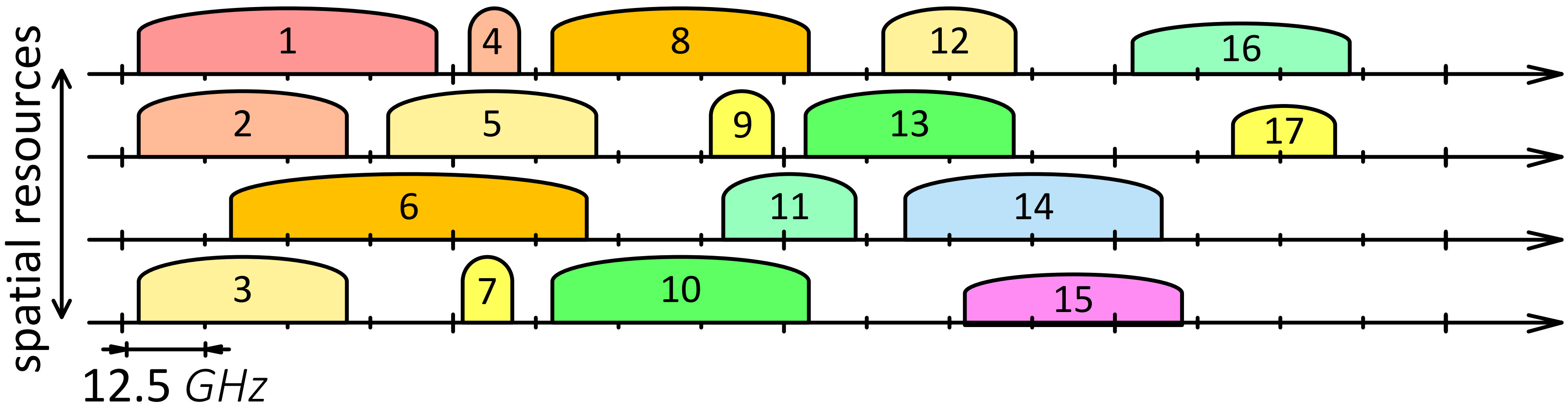
- **Multimode fiber** – fibers with a single, large core, which can carry additional optically-guided spatial modes, few-mode fibers (FMFs) offer a potential capacity multiplier equal to the mode count

SDM Scenarios

[*Spectral dimension/spatial dimension*]

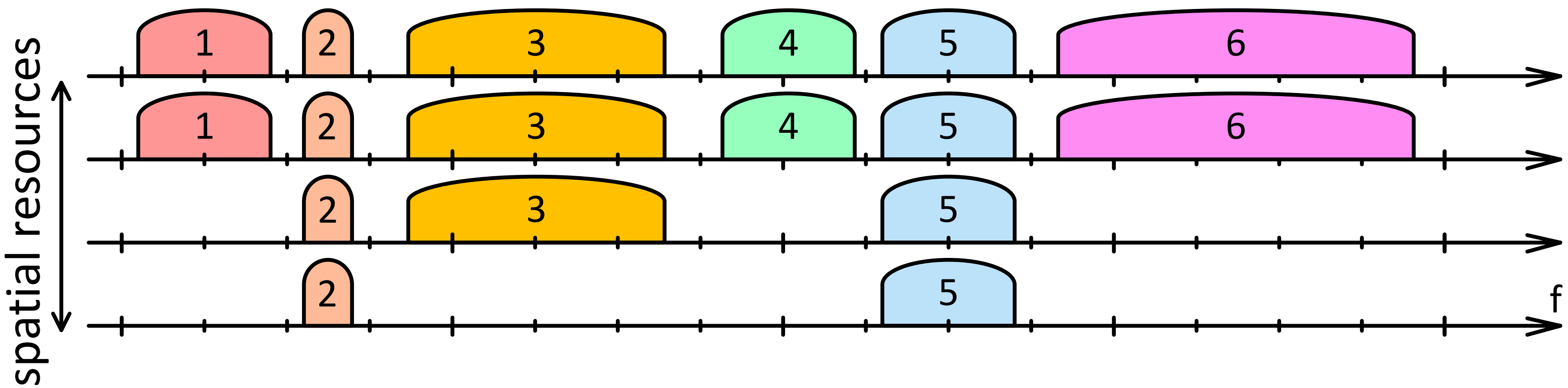
- **Flexgrid/Single** – parallel transmission in EON network
- **Flexgrid/Fixed** – SSChs can be transmitted using different SpRcs, however, within the same spectrum segment
- **Flexgrid/Flexible** – full spectral and spatial flexibility in forming SSChs is allowed. Although this scenario enables best resource utilization, it may lead to fragmentation of spectrum

Flexgrid/Single Scenario



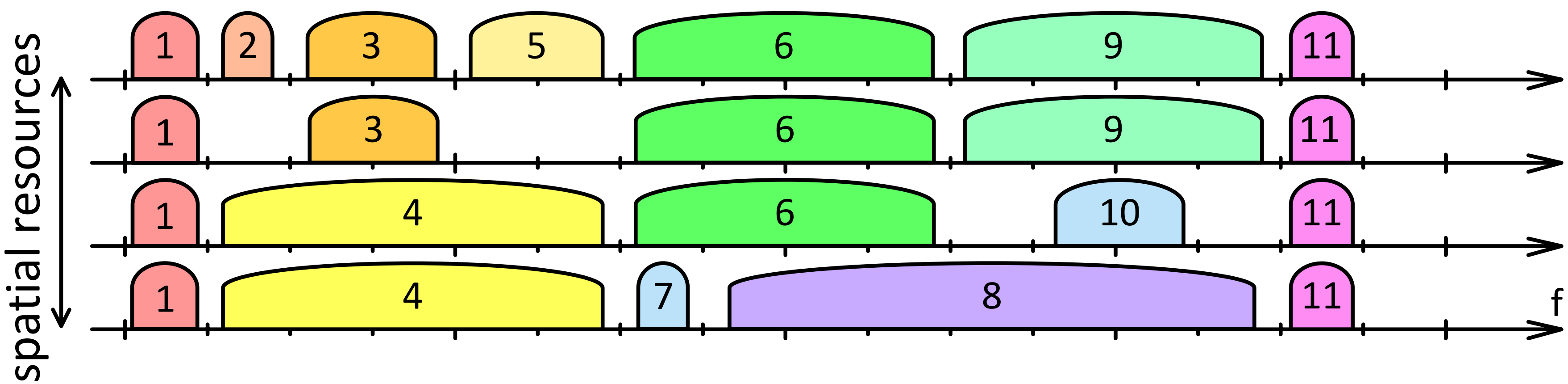
Independent switching of spatial mode and wavelength channel (i.e., space–wavelength granularity)

Flex-grid/Fixed Scenario



Wavelength switching across all spatial modes (wavelength granularity), also called **spectral switching** or **joint switching**

Flex-grid/Flexible Scenario



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**

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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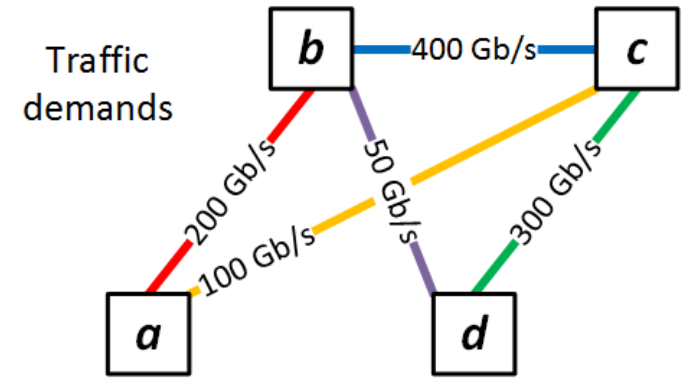
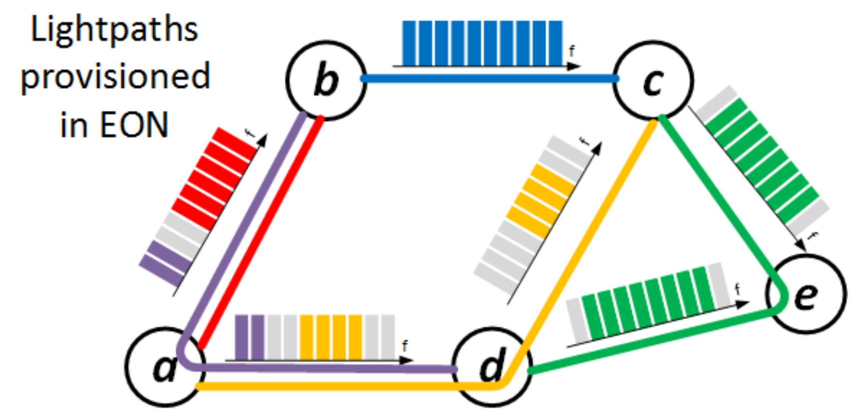
Routing and Spectrum Allocation (RSA)

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

DAT - Example

Distance-Adaptive Modulation Formats for Bit-Rate 400 Gb/s

	BPSK	QPSK	8-QAM	16-QAM
#transceivers	8	4	3	2
#slices	25	13	10	7
Range [km]	6 300	3 500	1 200	600

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)**

[Walkowiak K., Lechowicz P., Klinkowski M., Sen A., ILP Modeling of Flexgrid SDM Optical Networks, Proceedings of the 17th International Telecommunications Network Strategy and Planning Symposium **Networks 2016**, (Montreal, Canada, September 26-28, 2016), 2016]

SDM – Example (1)

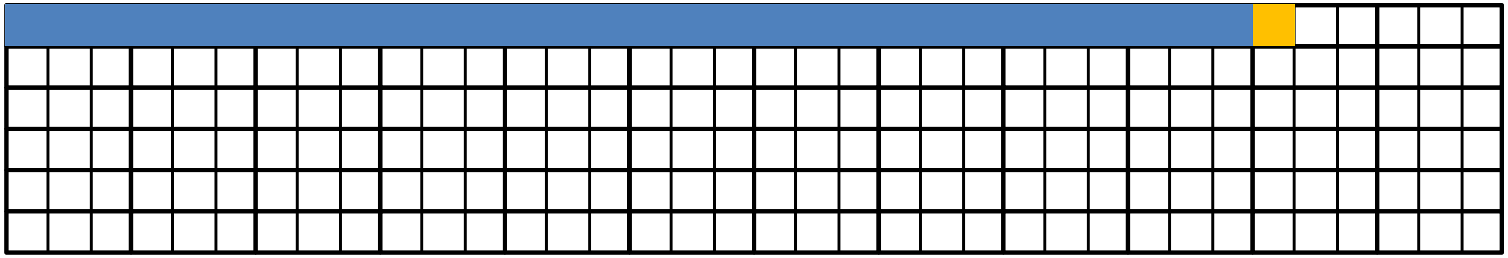
- Demand bit-rate is **1 Tbps**
- Path length is **3000 km**
- According to DAT, the selected MF is **QPSK**
- Since QPSK supports 100 Gbps per one transceiver, we need **10** transceivers (=1 Tbps/100 Gbps) and **30** slices of 12.5 GHz

SDM – Example (2)

30 slices required to etablish 1 Tbps demand using QPSK on 3000 km path

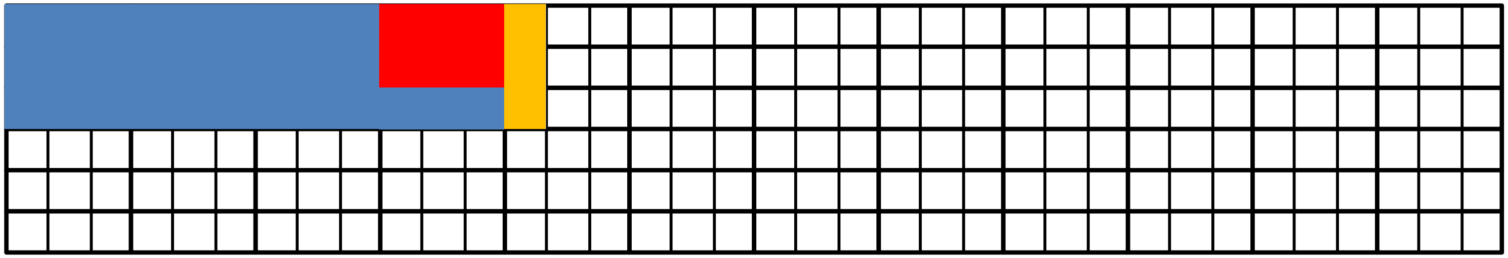
SSCh on **1 SpRcs**

31=30+1



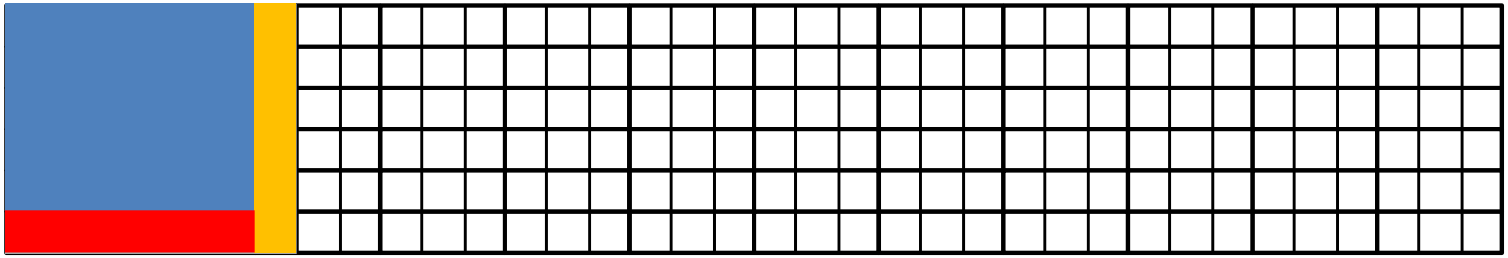
SSCh on **3 SpRcs**

39=30+6+3



SSCh on **6 SpRcs**

42=30+6+6



ILP Model

objective

min $\sum_{s \in S} y_s$

constraints

$\sum_{p \in P(d)} \sum_{c \in C(d,p)} x_{dpc} = 1$ $\quad d \in D$

$\sum_{d \in D} \sum_{p \in P(d)} \sum_{c \in C(d,p)} \gamma_{dpcsk} \delta_{edp} x_{dpc} \leq y_{esk}$ $\quad e \in E,\ k \in K(e),\ s \in S$

$\sum_{k \in K(e)} y_{esk} \leq |K(e)| y_{es}$ $\quad e \in E,\ s \in S$

$\sum_{e \in E} y_{es} \leq |E| y_s$ $\quad s \in S$

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Greedy Algorithm

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

```
function Greedy(D, P, comp, sort)
        D := sortDemands(D, sort)
        for i := 0 to |D| do
        d := D[i]
        [p, ssch] := FPCSpectrum(P(d); comp)
        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:

$$\boldsymbol{\Theta_1(c) = \alpha\,(guardband(c) + rounding(c)) + end(c)}$$

- Demands-Varying Penalty (DVP) — the SSCh with the lowest penalty $\Theta_2(c)$ is selected:

$$\boldsymbol{\Theta_2(c) = \alpha\cdot(1-\tau)\cdot(guardband(c) + rounding(c)) + (1-\alpha)\cdot\tau\cdot end(c)}$$

- ***end*(*SSCh*)** returns an index of the highest slice used by SSCh
- ***rounding*(*SSCh*)** returns the amount of slices wasted for rounding
- ***guardband*(*SSCh*)** returns the amount of slices used for guardbands
- τ is equal to the ratio of currently allocated demands to all demands

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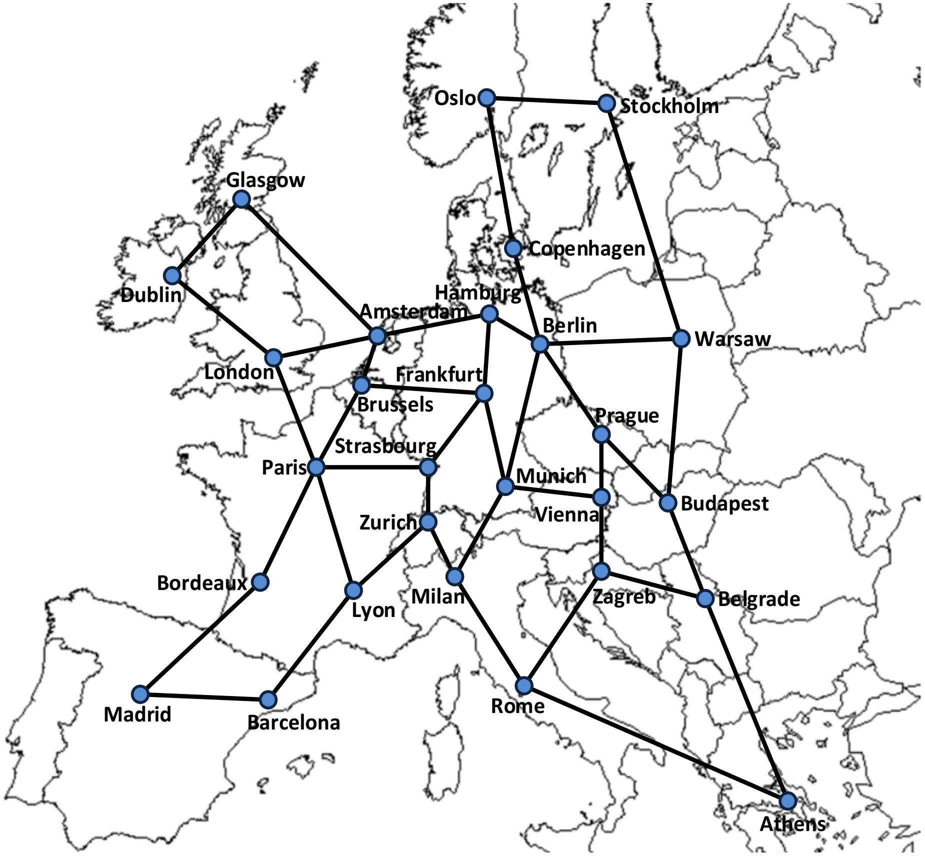
Assumptions

- **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

Topologies



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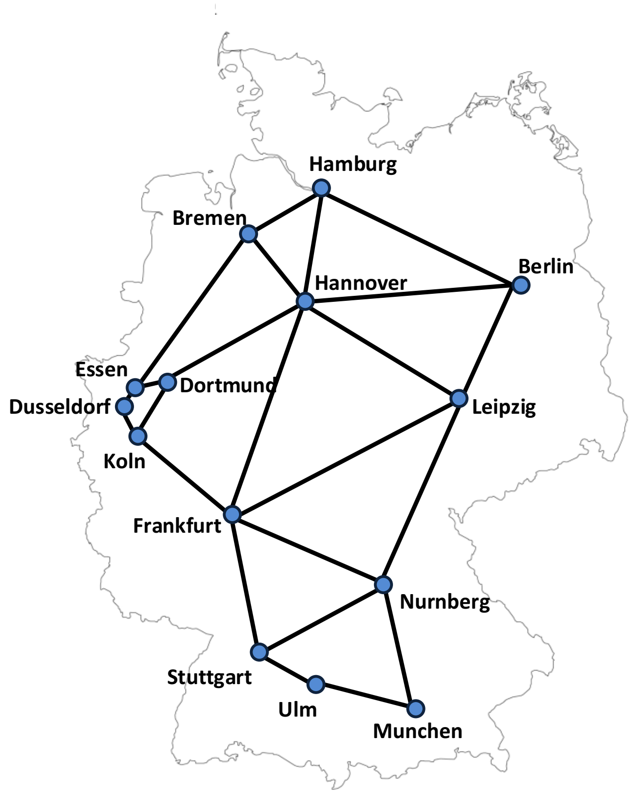

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Dusseldorf
Leipzig
Koln
Frankfurt
Nurnberg
Stuttgart
Ulm
Munchen

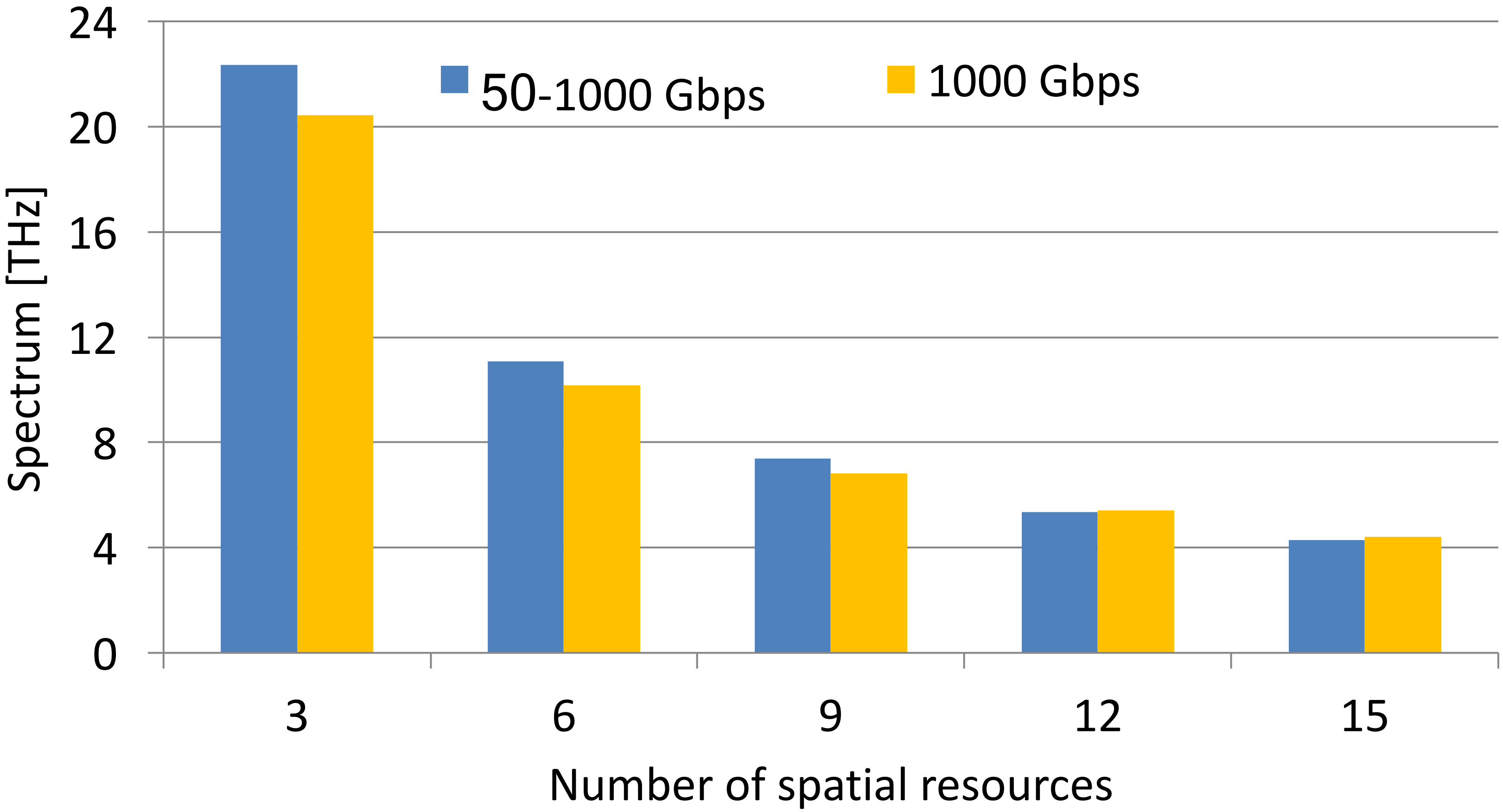
Tuning – Number of Slices

Algorithm	Sorting		
	Slice	Distance	Hop Count
LS	**1066.1**	1125.8	1079.5
LE	1300.8	1367.3	1331.3
PEN(α=0.2)	1300.1	1366.7	1335.5
PEN(α=0.5)	1301.4	1365.3	1332.6
PEN(α=0.8)	1264.1	1323	1288.1
DVP(α=0.2)	1236.7	1319	1278.6
DVP(α=0.5)	1202.3	1274.1	1230.6
DVP(α=0.8)	1159	1217.5	1157.7

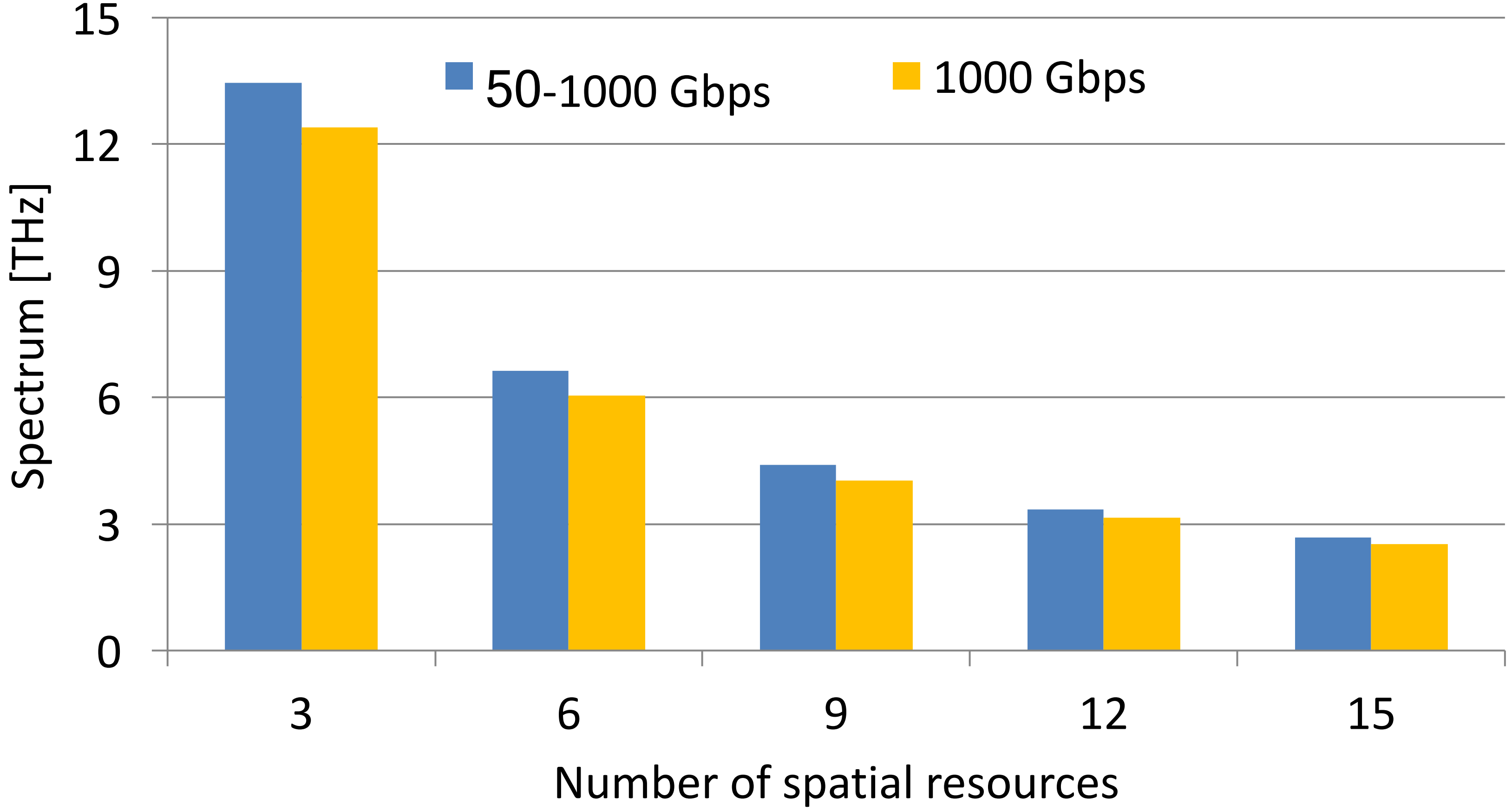
CPLEX vs. Heuristic for Euro28

$\lvert P(d) \rvert$	$\lvert D \rvert$	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

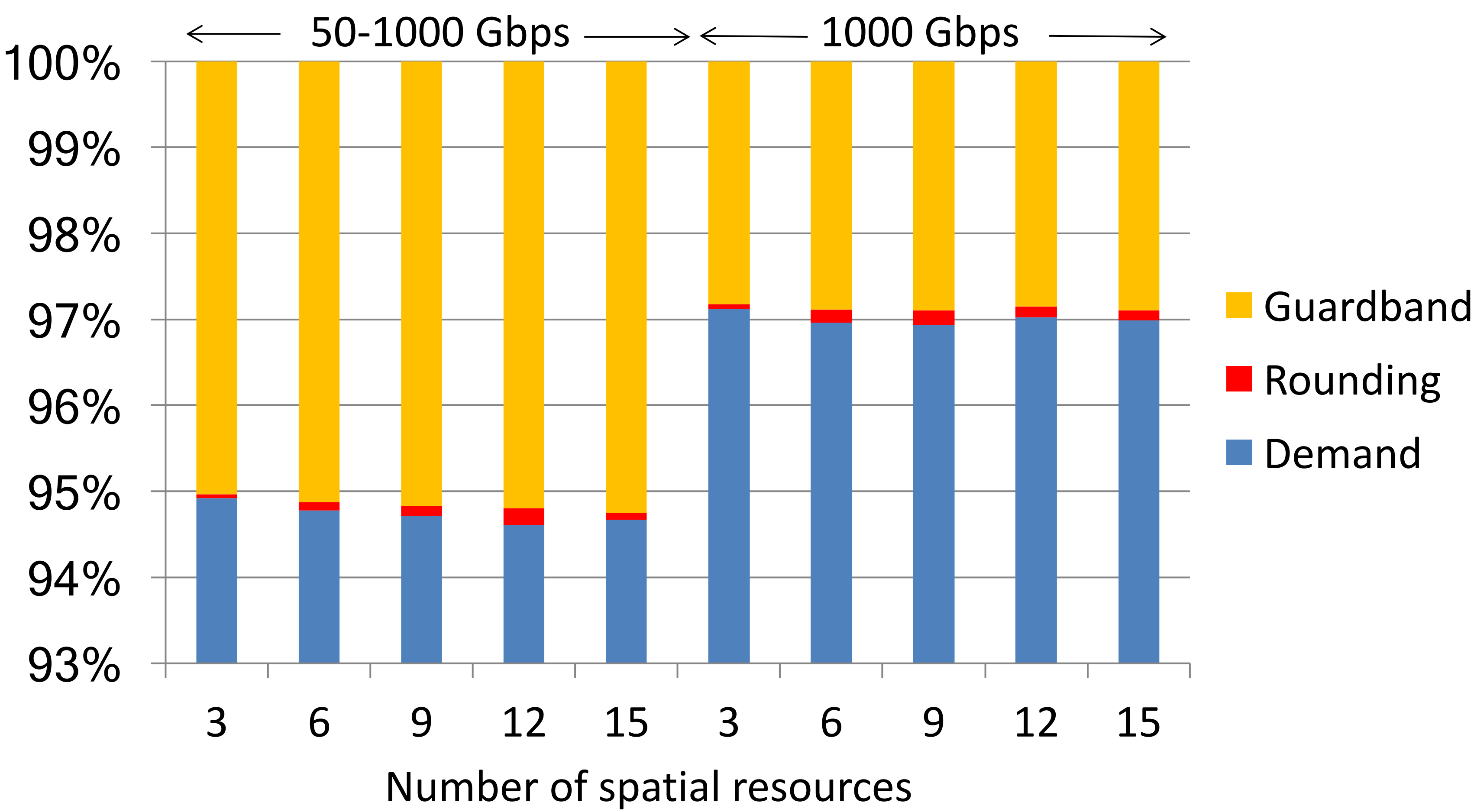
Spectrum usage for various types of demands – network Euro28 and 1 Pbps traffic



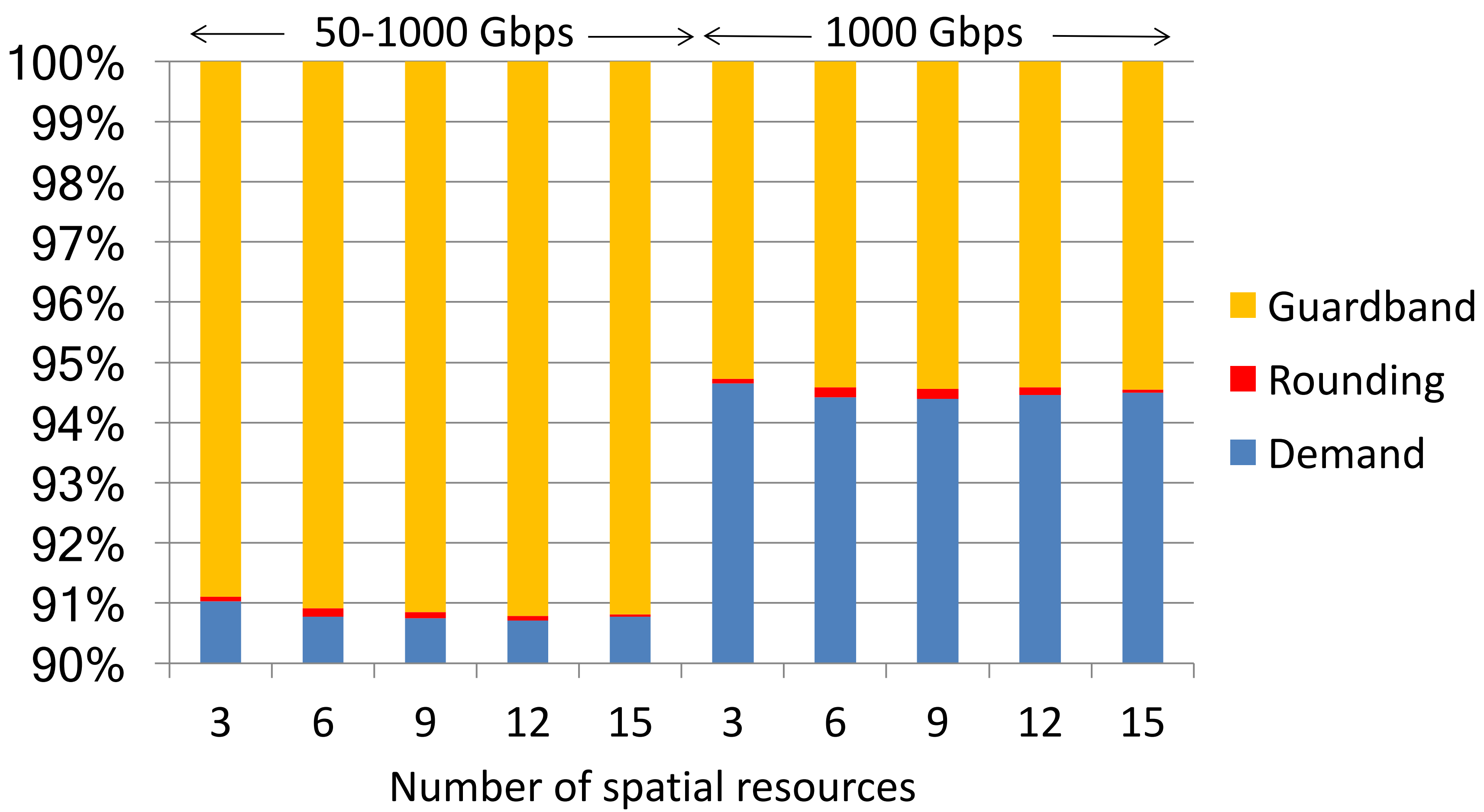
Spectrum usage for various types of demands – network DT14 and 1 Pbps traffic



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



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



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K. Walkowiak, "Selection of Spectral-Spatial Channels in SDM Flexgrid ...", ONDM2017

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

Network	Number of spatial resources				
	3	6	9	12	15
Euro28	2	11	63	325	1691
DT14	1	7	28	133	621

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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**

Thank you for attention

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