Wrocław University of Technology

How to overcome the capacity crunch – new challenges in optical networks

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Agenda

- Introduction
- Solutions
- Evolution of Optical Networks
- Optimization of Elastic Optical Networks
- Case Study
- Conclusions

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Wrocław

- 4th city in Poland, population 600 000
- European Capital of Culture 2016
- Soccer UEFA European Championship 2012

Wrocław University of Technology

- Wrocław University of Technology is an **inheritor** of the property of the **German Königliche Technische Hochschule Breslau** and the intellectual and research traditions of the **Lvov Polytechnic**

- The university has been functioning under the current name since **1945**, it was established and organized by researchers from **Lvov and Warsaw**

Wrocław University of Technology

- Today, it belongs to the **best technical universities in Poland** – over 32 000 students and 2 000 academic teachers, at the 12 faculties
- It rates **high in the annual rankings** of Polish universities

- Owing to the Wrocław Univeristy of Technology, Wrocław appears as the **capital of Polish computer science**

Acknowledgments

- European Commission under the FP7 Project ENGINE - European research centre of Network intelliGence for INnovation Enhancement (http://engine.pwr.wroc.pl/)
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- **Michał Aibin**, PhD Student

Capacity Crunch – Why???

- **Bandwidth-hungry applications/services:**
  - HDTV, video streaming Netflix available in Poland since 2016 :)
  - 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

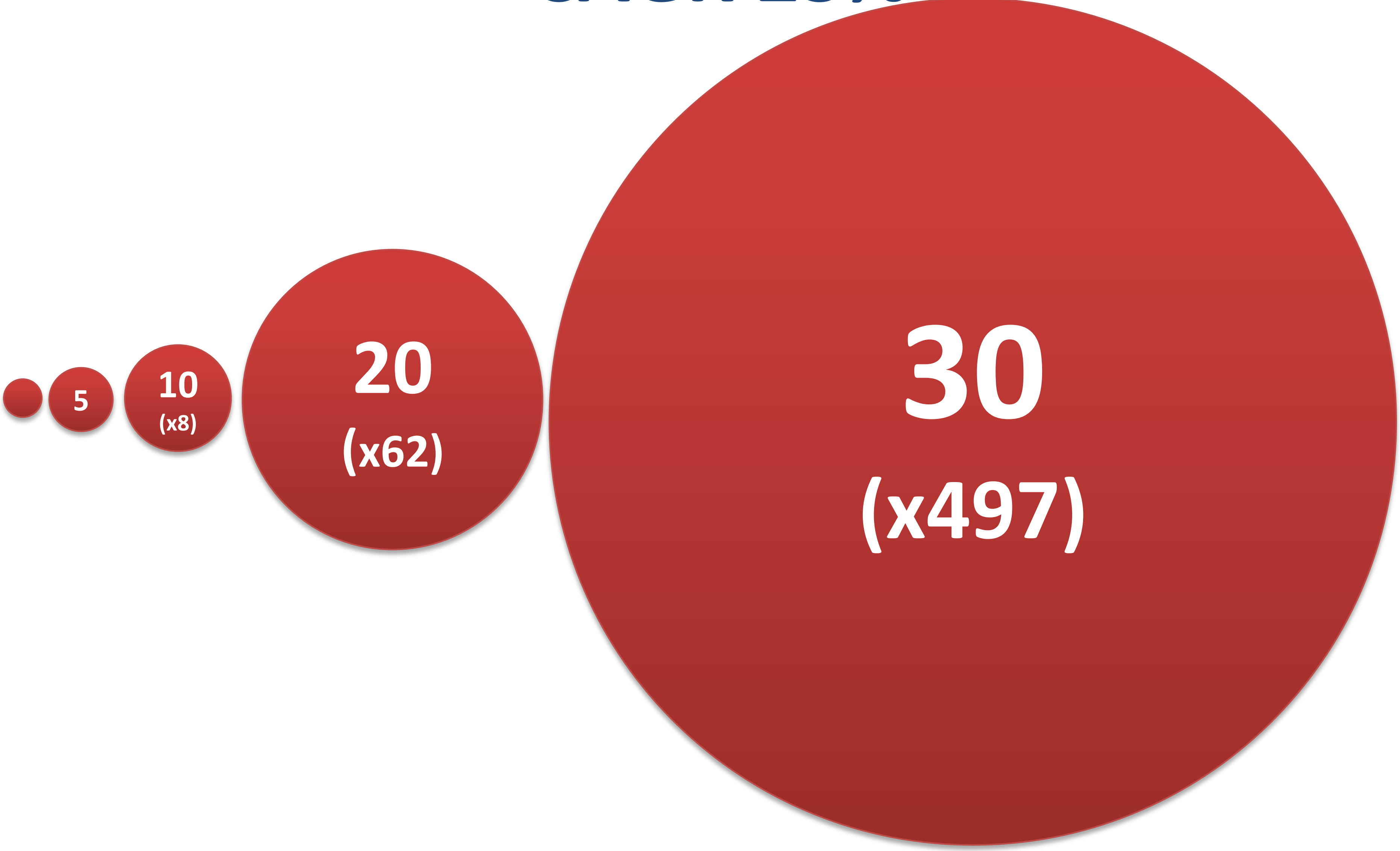
IP Traffic

- 2012: VNI report for years 2011-2016 report, **CAGR=29%**
- 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%**

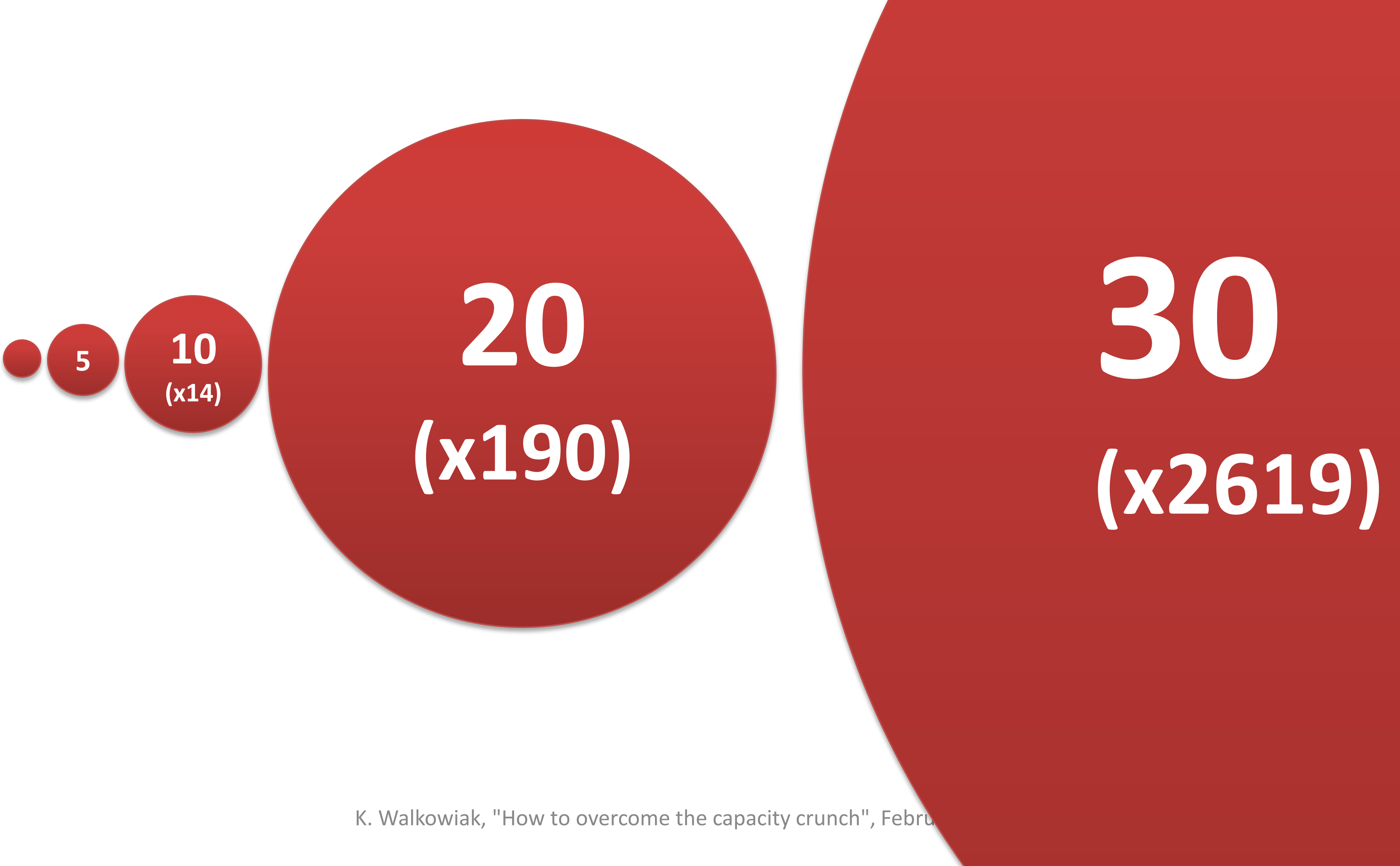
Content Delivery Network (CDN) Traffic

- 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%**

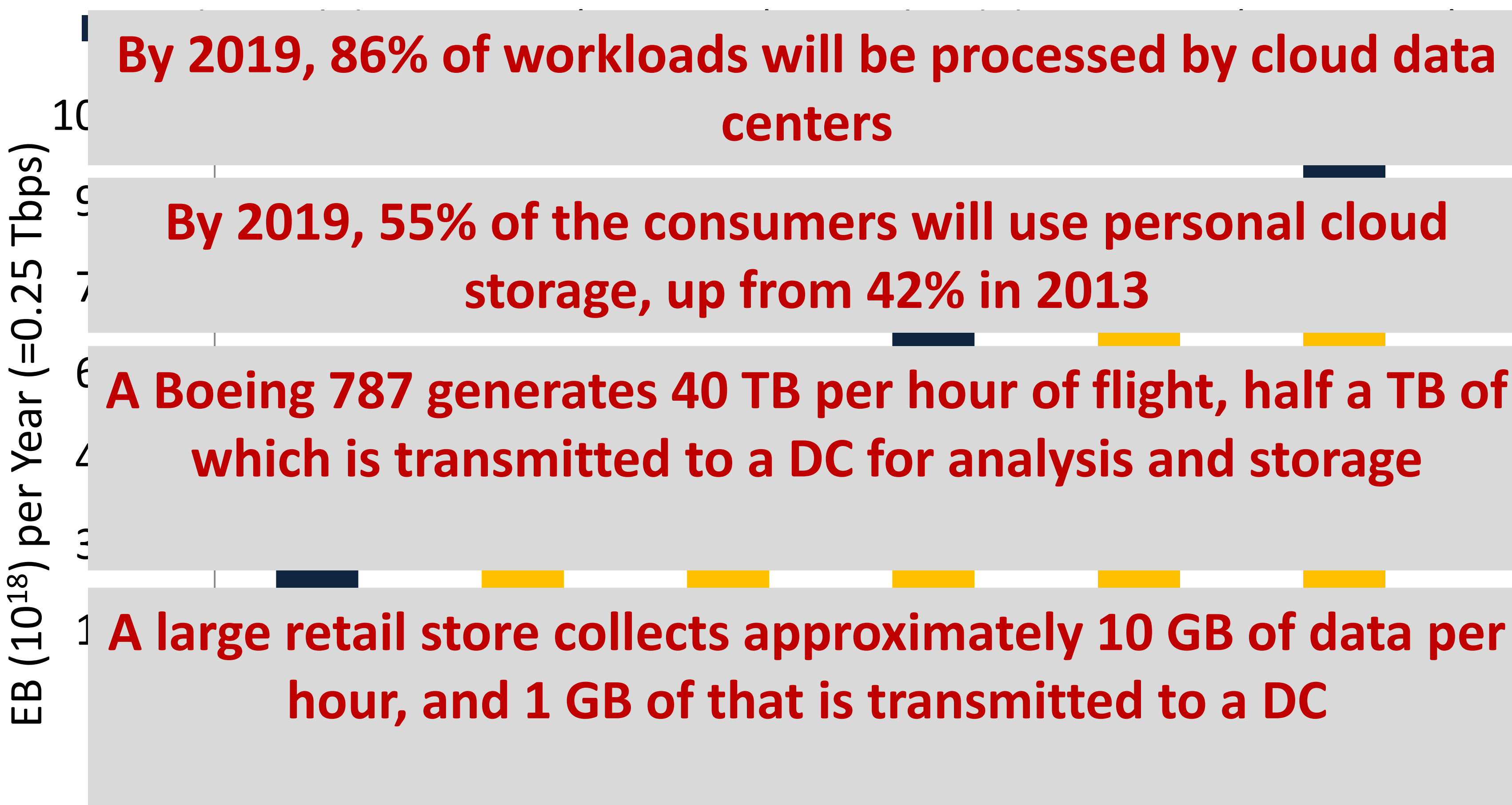
CAGR 23%



CAGR 30%



Data Center Traffic



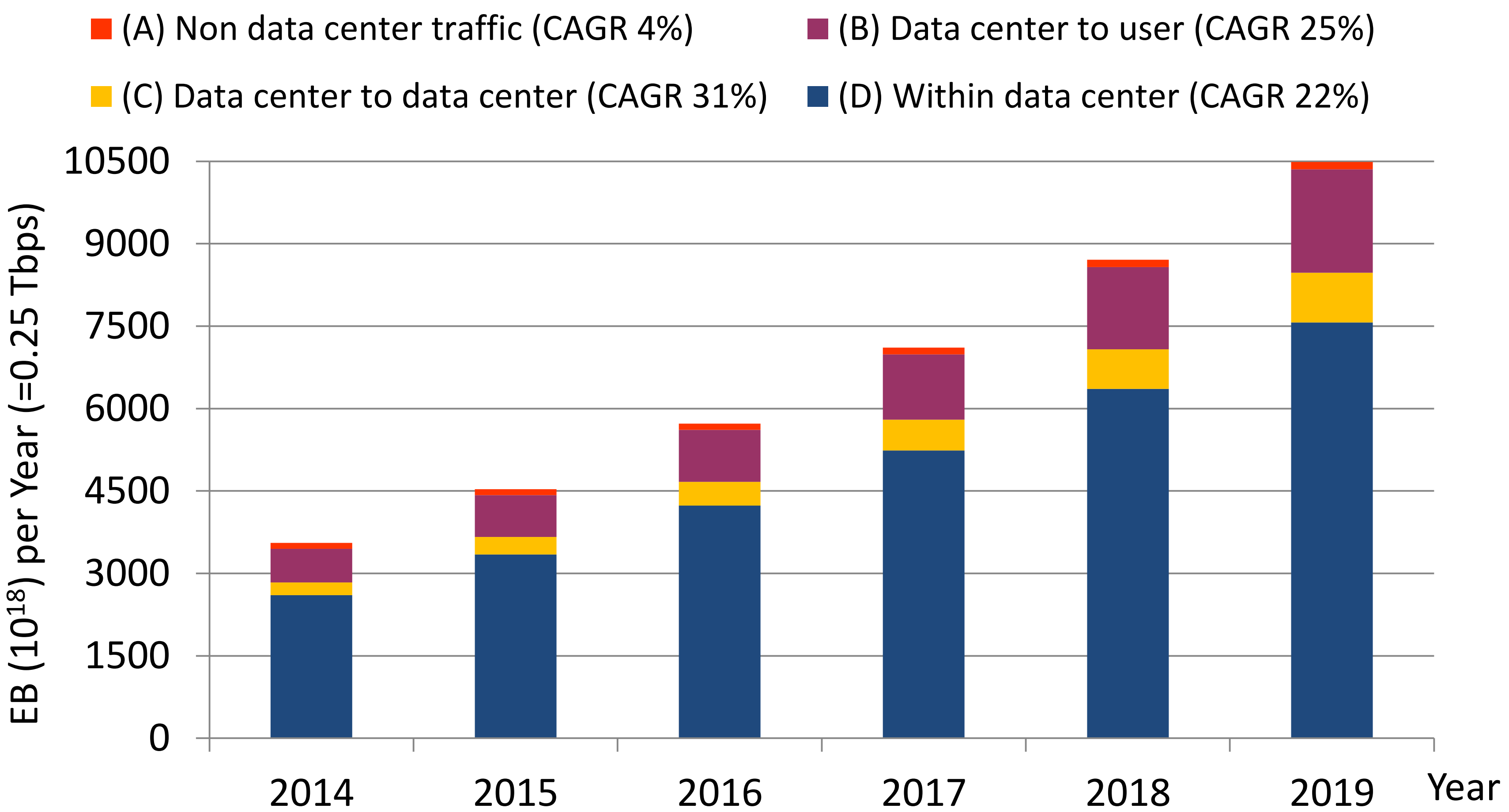
By 2019, 86% of workloads will be processed by cloud data centers

By 2019, 55% of the consumers will use personal cloud storage, up from 42% in 2013

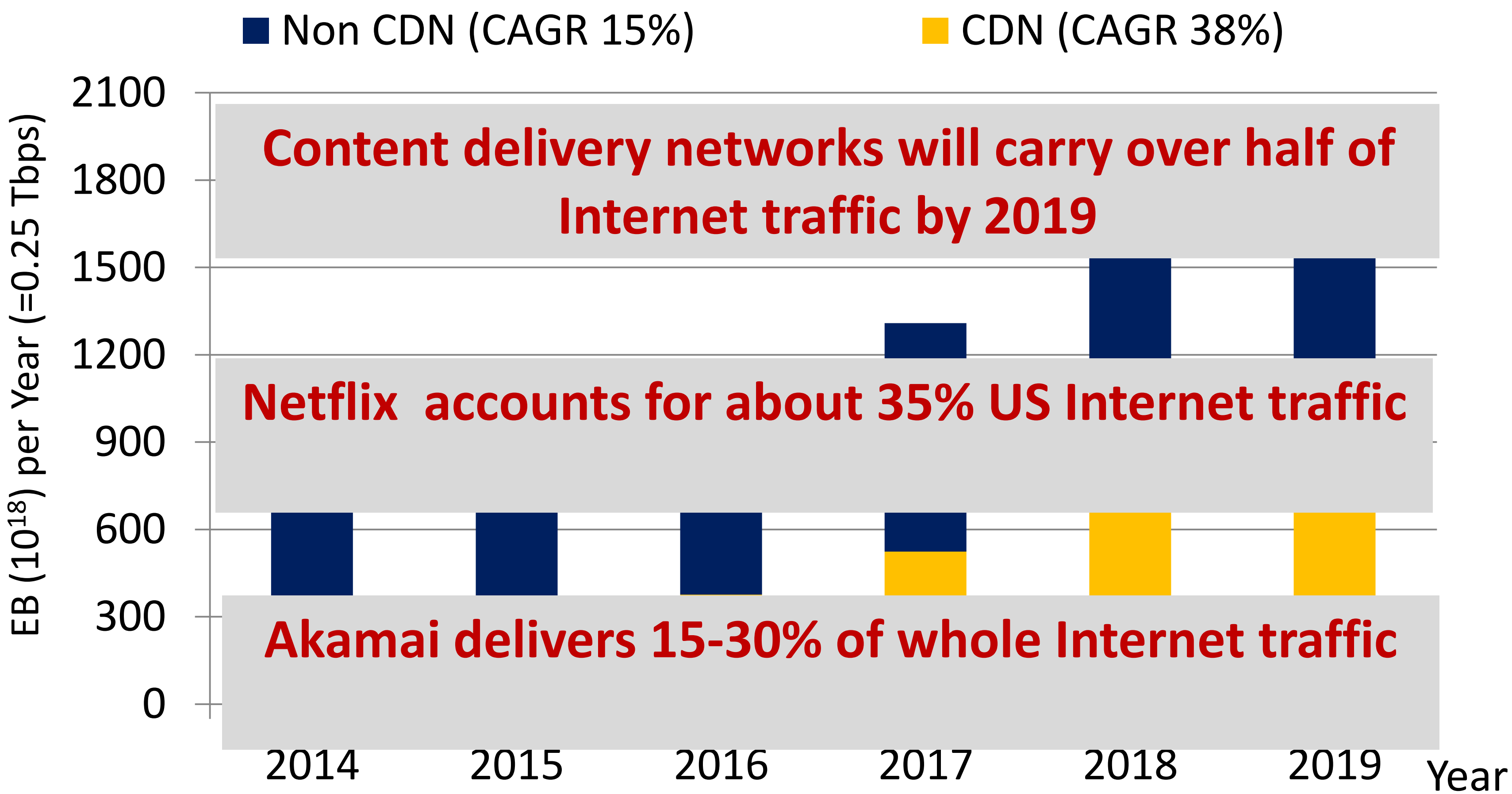
A Boeing 787 generates 40 TB per hour of flight, half a TB of which is transmitted to a DC for analysis and storage

A large retail store collects approximately 10 GB of data per hour, and 1 GB of that is transmitted to a DC

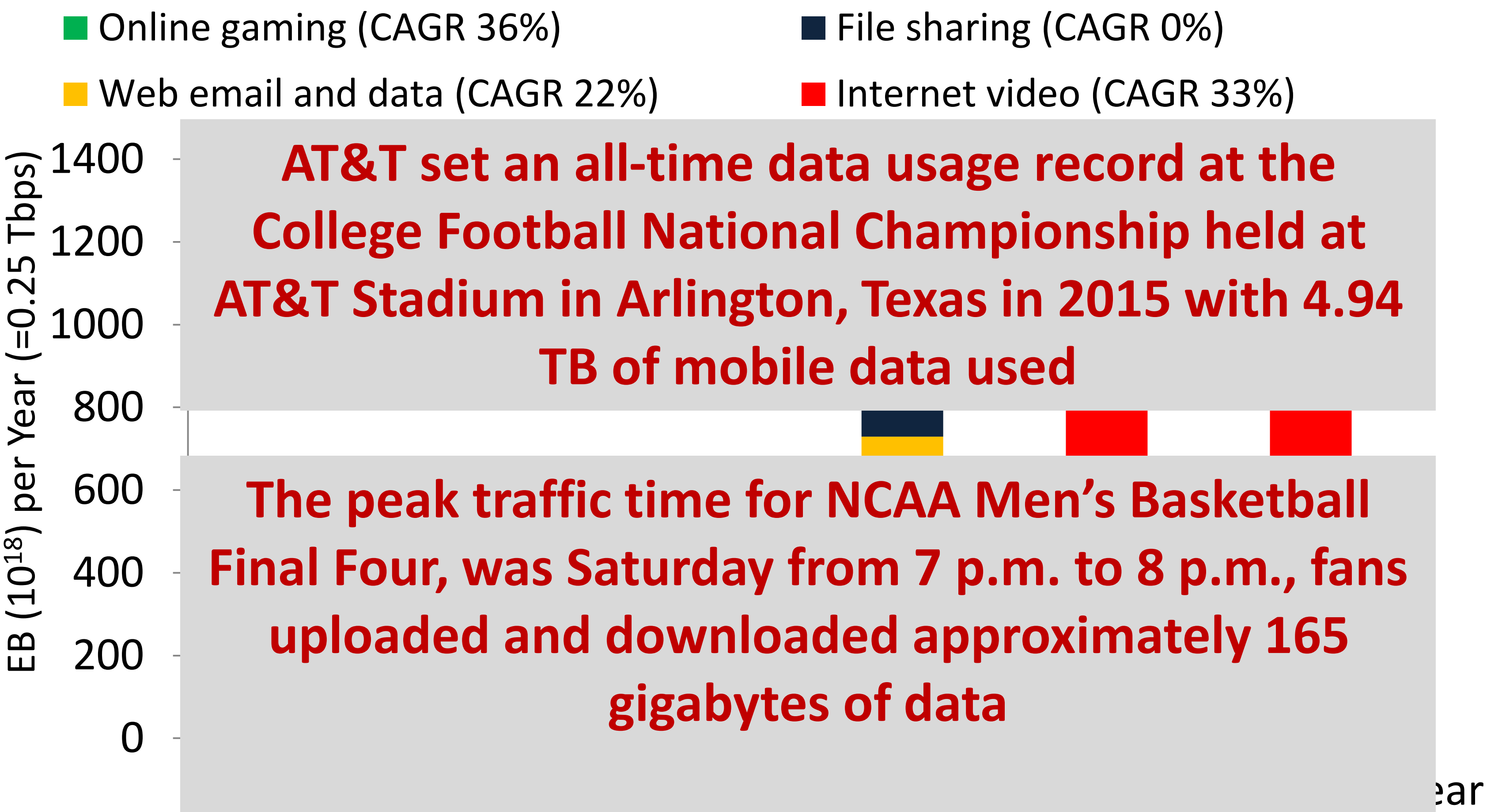
Data Center Traffic



CDN Traffic


Non CDN (CAGR 15%)
CDN (CAGR 38%)
2100
1800
1500
1200
900
600
300
0
EB (10^{18}) per Year (=0.25 Tbps)
Content delivery networks will carry over half of Internet traffic by 2019
Netflix accounts for about 35% US Internet traffic
Akamai delivers 15-30% of whole Internet traffic
2014
2015
2016
2017
2018
2019
Year

Internet Consumer Traffic



AT&T set an all-time data usage record at the College Football National Championship held at AT&T Stadium in Arlington, Texas in 2015 with 4.94 TB of mobile data used

The peak traffic time for NCAA Men's Basketball Final Four, was Saturday from 7 p.m. to 8 p.m., fans uploaded and downloaded approximately 165 gigabytes of data

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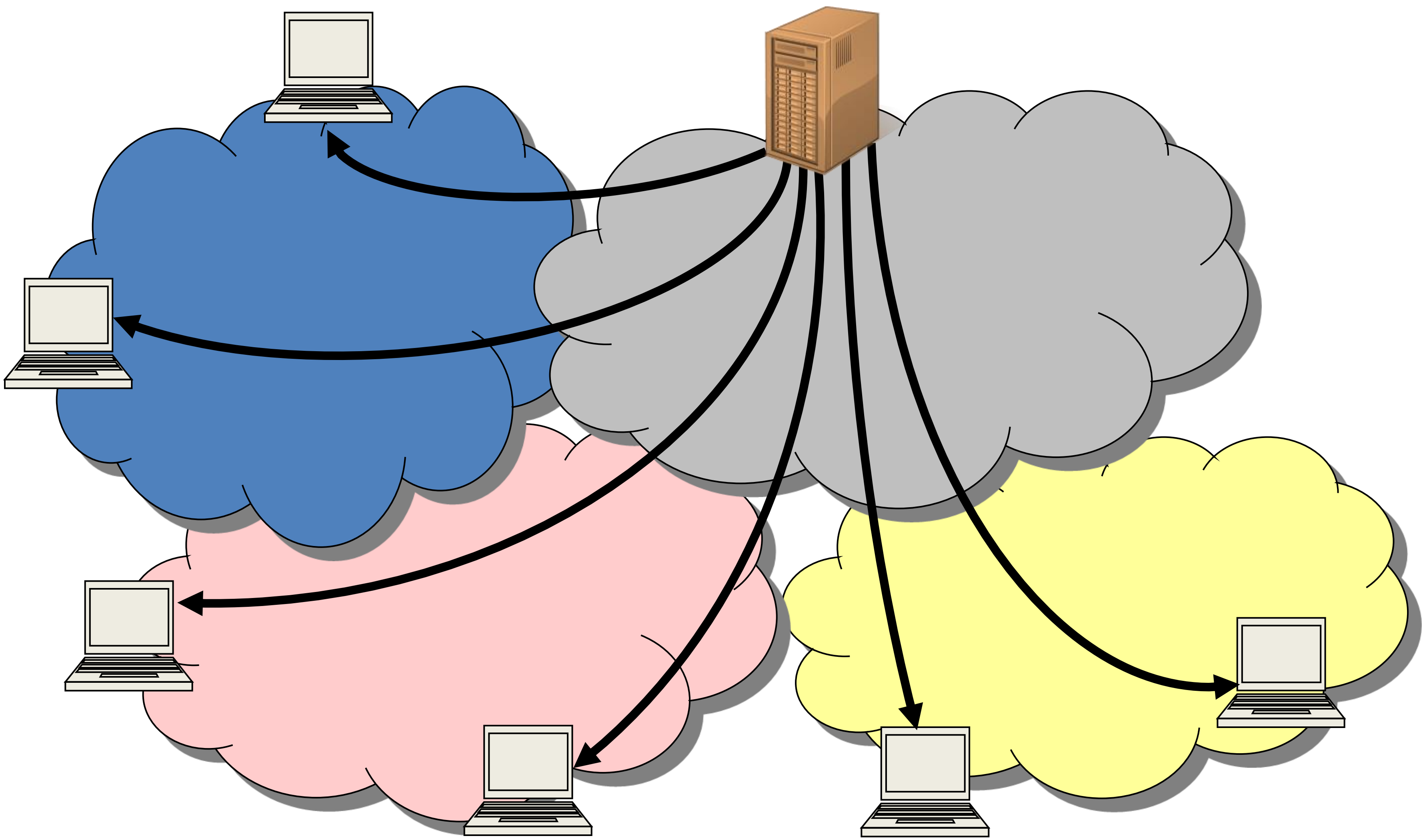
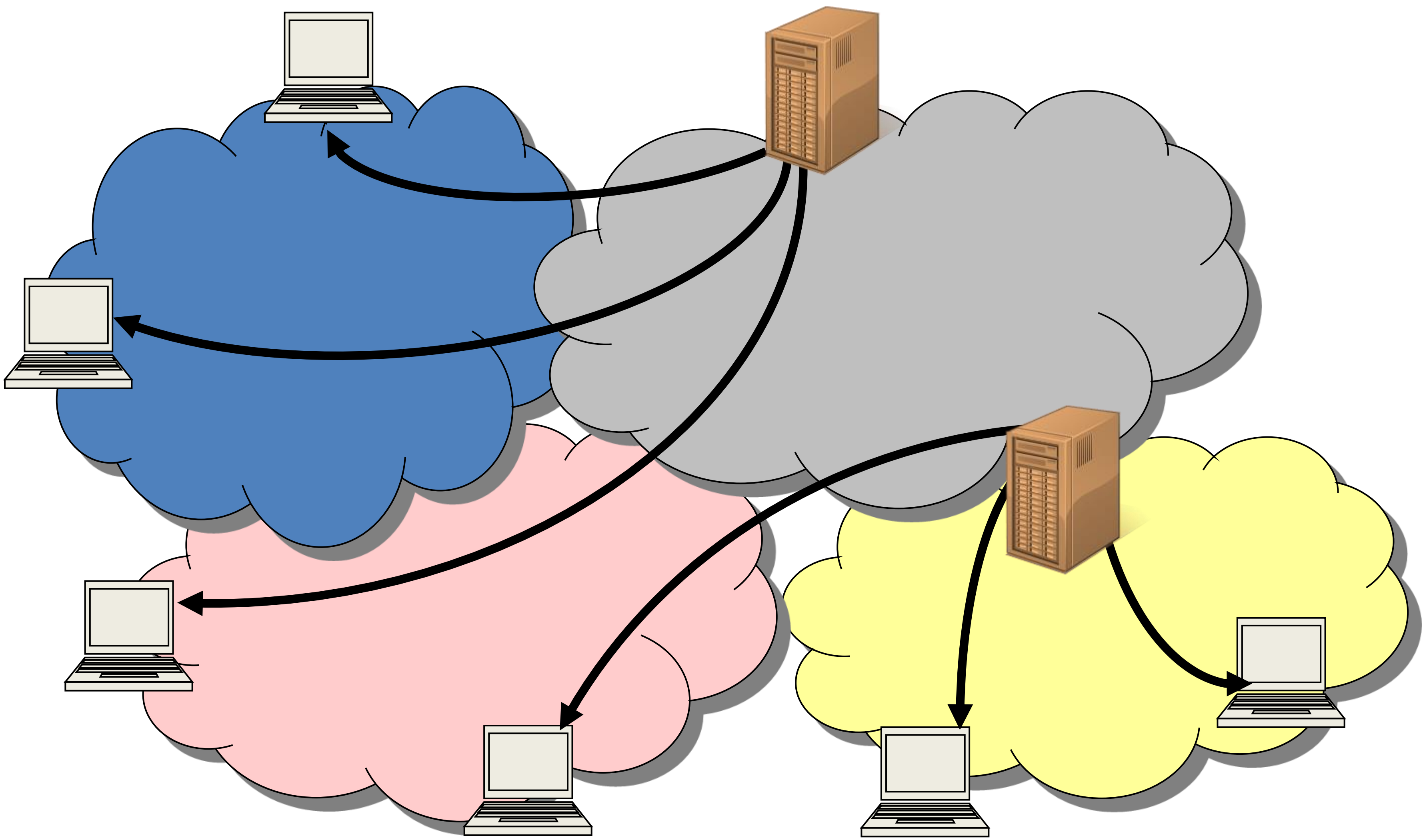
How to overcome the capacity crunch???

Deliver network traffic in a smart way

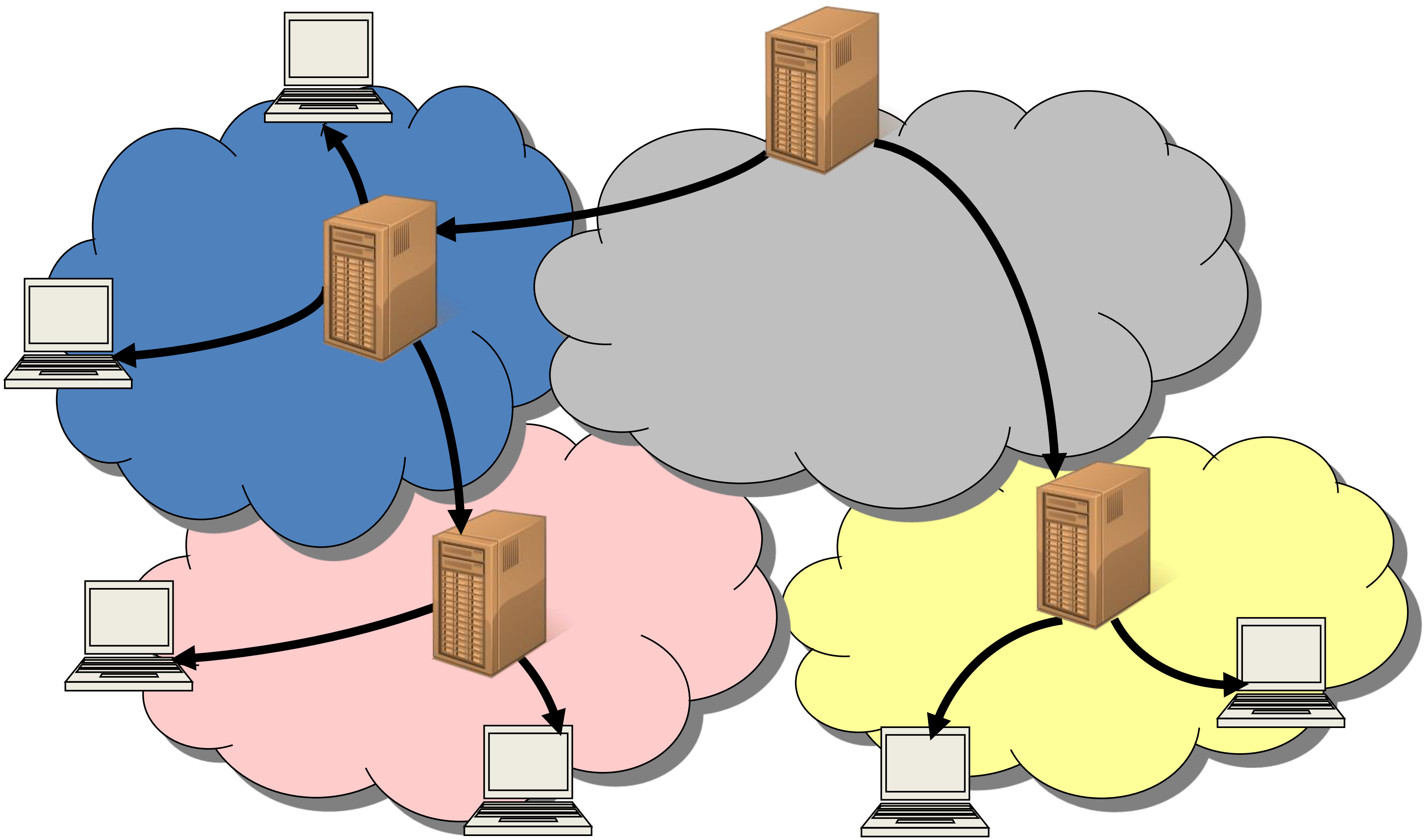
Unicast (one server)



Anycast (many servers)

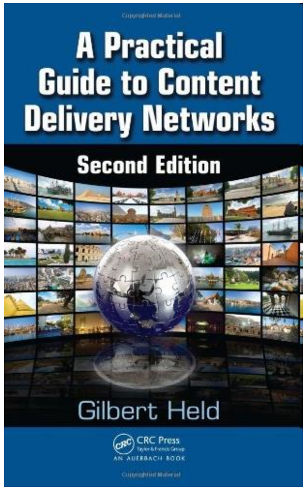


Multicast / Content Oriented Network



Content Delivery Network (CDN)

- „A **content delivery network** represents a group of geographically disparsed servers deployed to facilitate the distribution of information generated by Web publishers in a timely and efficient manner”



„A **content delivery network** or content distribution network (CDN) is a system of computers containing copies of data placed at various nodes of a network. (…) Data content types often cached in CDNs include web objects, downloadable objects (media files, software, documents), applications, live streaming media, and database queries”

CDN Providers

- Akamai
- Limelight
- CloudFare
- Big players have their own CDNs, e.g., Google, Netflix, Microsoft, Facebook, Amazon, Alibaba
- Telecoms also have their own CDNs

More Network Intelligence

- Traffic engineering (e.g. MPLS)
- SDN (Software Defined Networking)
- …

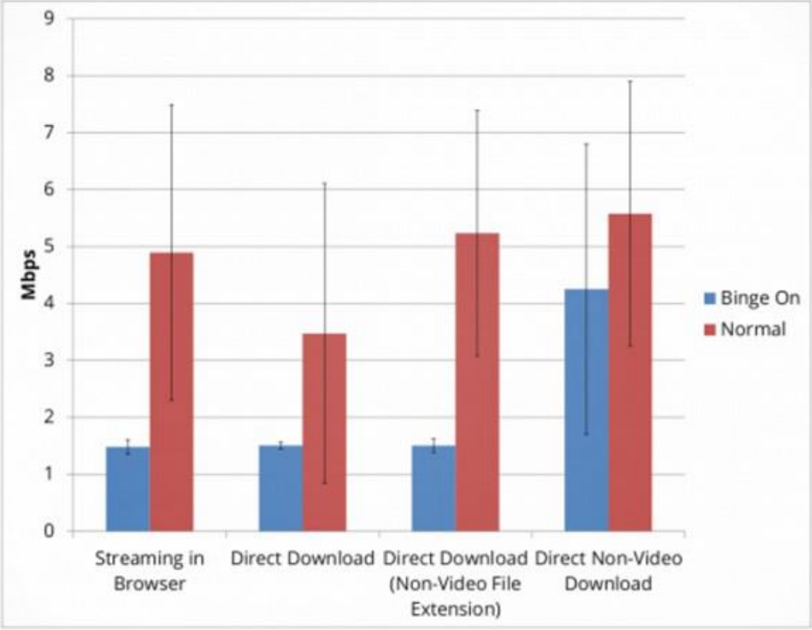
Limit network traffic

Peer-to-Peer Systems

- Many telecoms and ISPs **block/limit P2P traffic**
- Thus, according to the recent Cisco VNI report, the **file sharing traffic (including P2P systems) will be stable (CAGR=0%)** in years 2014-2019

Throttling

- T-Mobile US **Binge On is a zero-rating service** and users (mobile access) are **FREE to stream unlimited video** on favorite services like Netflix, HBO NOW without using a drop of data
- However, this service **throttles the quality of the stream** to about 1.5Mbps
- **T-Mobile US claims** it is a "DVD quality" of at least 480p resolution
- Some specialist claim that Binge On **violates net neutrality**
- Video providers try to „hide" signal (e.g. **encrypt**) to avoid throttling



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Evolution of Optical Networks

- **Currently**, most of the **transport optical networks use WDM** (Wavelength Division Multiplexing) technology
- Possible ways to increase capacity of optical networks:
  - **Elastic Optical Networks (EONs)** with higher flexibility in the spectrum domain
  - **Space-Division Multiplexing (SDM)** with higher flexibility in the space domain

WDM

- **WDM (Wavelength Division Multiplexing)** is an optical technology, which multiplexes optical signals on a single optical fiber by using different **wavelengths (colors)** of laser light to carry different signal
- **Wavelength Switched Optical Networks (WSON)** architectures using WDM enable all-optical transmission and switching of data streams of 10 Gb/s, 40 Gb/s, and, recently, 100 Gb/s
- WSONs use a **fixed frequency grid** of **50 GHz** with **single-line-rate** transponders making use of **single-carrier modulation** techniques

Elastic Optical Networks

- EON is a **new idea of spectrally-efficient and flexible** optical transport networks that has been developed since 2009
- A technology that allowed the implementation of EONs is a **spectrum-sliced elastic optical path network (SLICE)** – an innovative and promising solution for new generation of optical network with capacity beyond 100 Gb/s

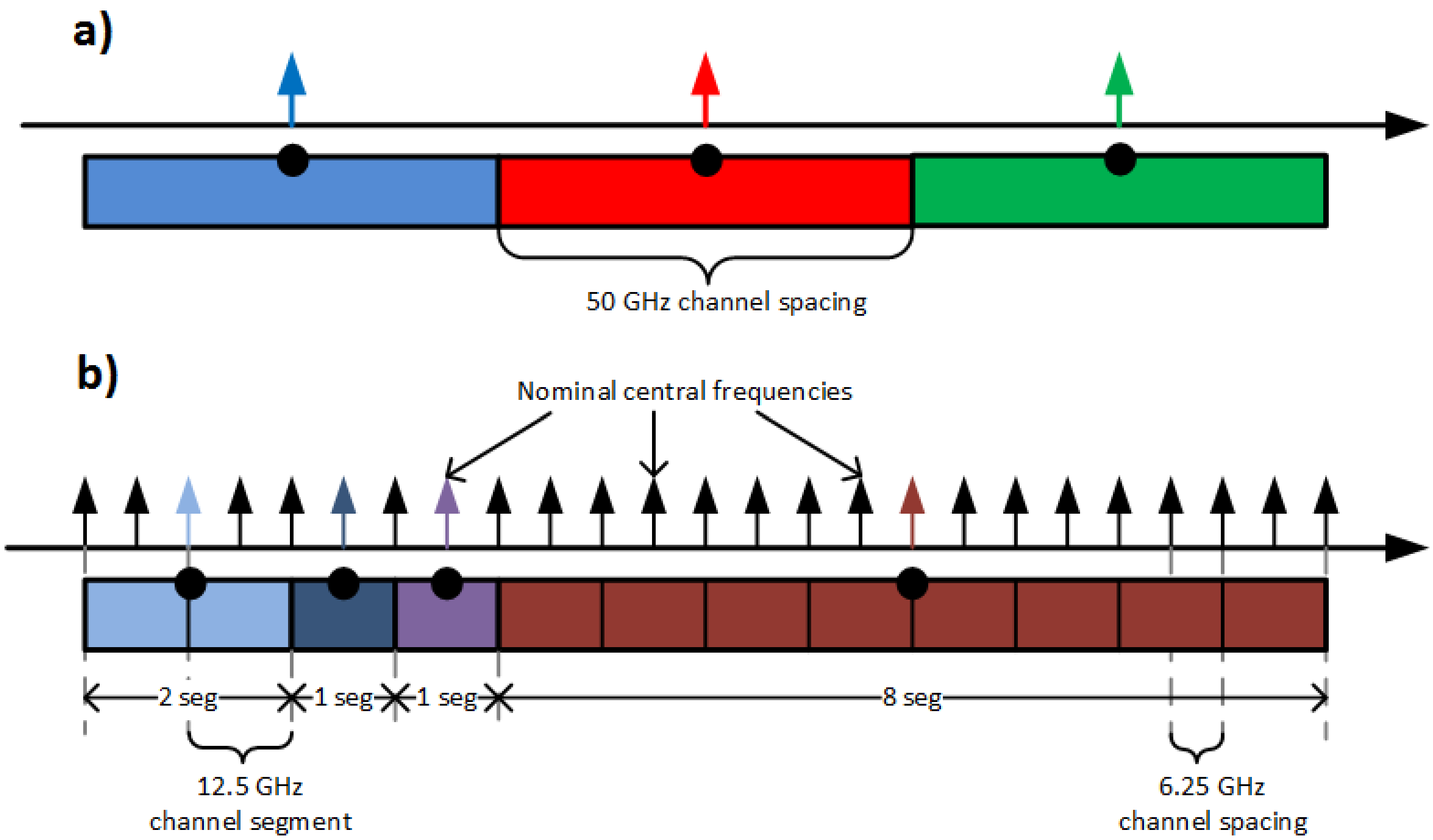
[M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and pp. Matsuoka. Spectrum efficient and scalable elastic optical path network: Architecture, benefits, and enabling technologies. IEEE Comm. Mag., 47(11):66–73, Nov. 2009]

- The **key advantage** of the SLICE architecture is supporting sub-wavelength, superwavelength and multiple-rate data traffic accommodation in a spectrum-efficient way

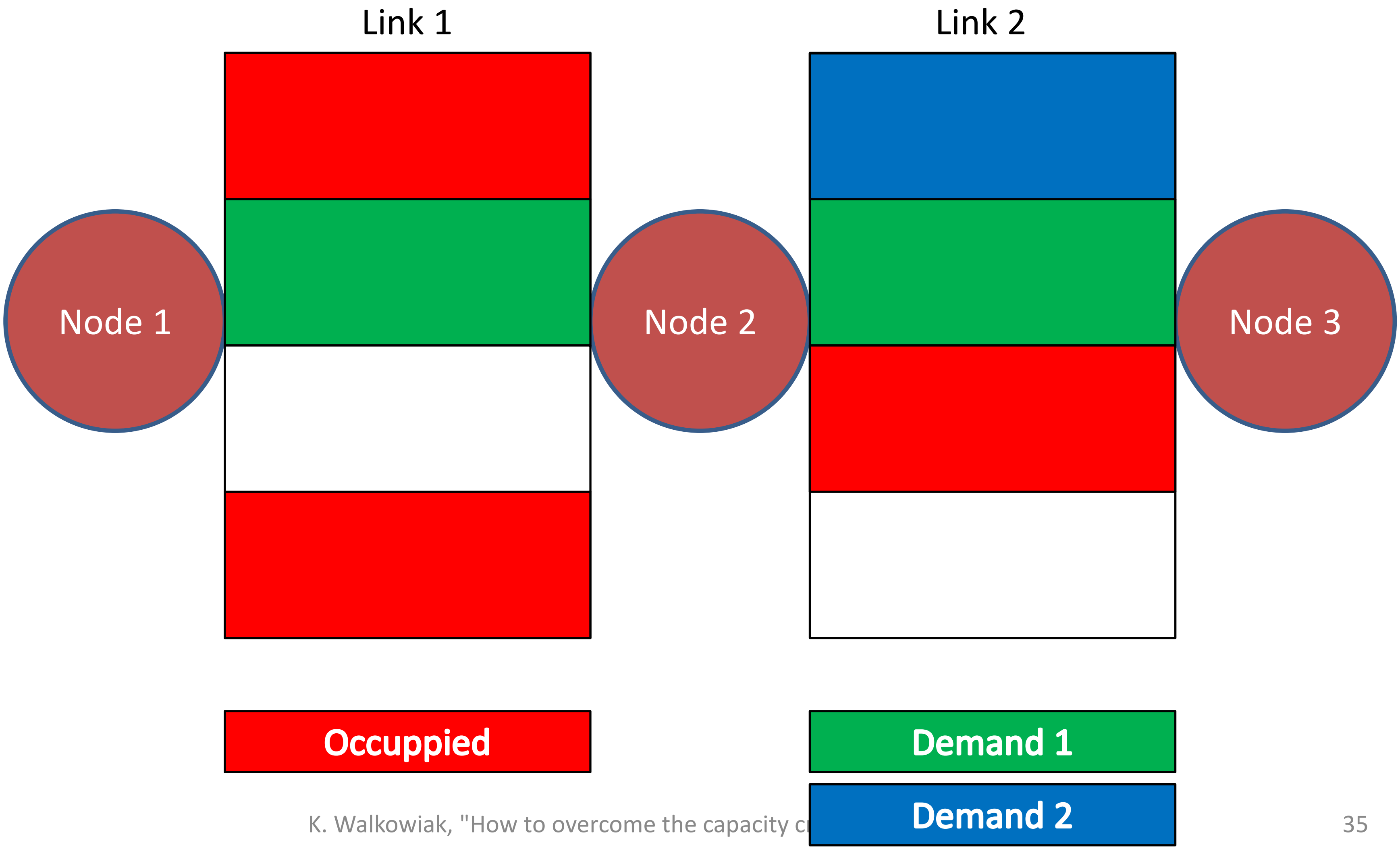
EON vs. WDM

- The key requirement for new optical technologies is **spectral efficiency**
- WDM systems have been addressing the traffic growth by **increasing the number of wavelengths** on a single fiber and by **increasing the bit-rate** provided by each wavelength
- However, the fixed grid of **50 GHz used in WDM** in practice limits the maximum wavelength bit-rate to **100 Gb/s**
- Therefore, a **flexible grid** architecture is adapted in EONs and a finer grid granularity is used
- The **ITU.G.694.1.2012 standard** permits any combination of wavelength spacing using **6.25 GHz slices** and the bandwidth assigned to a lightpath equals to integral multiple of **12.5 GHz**

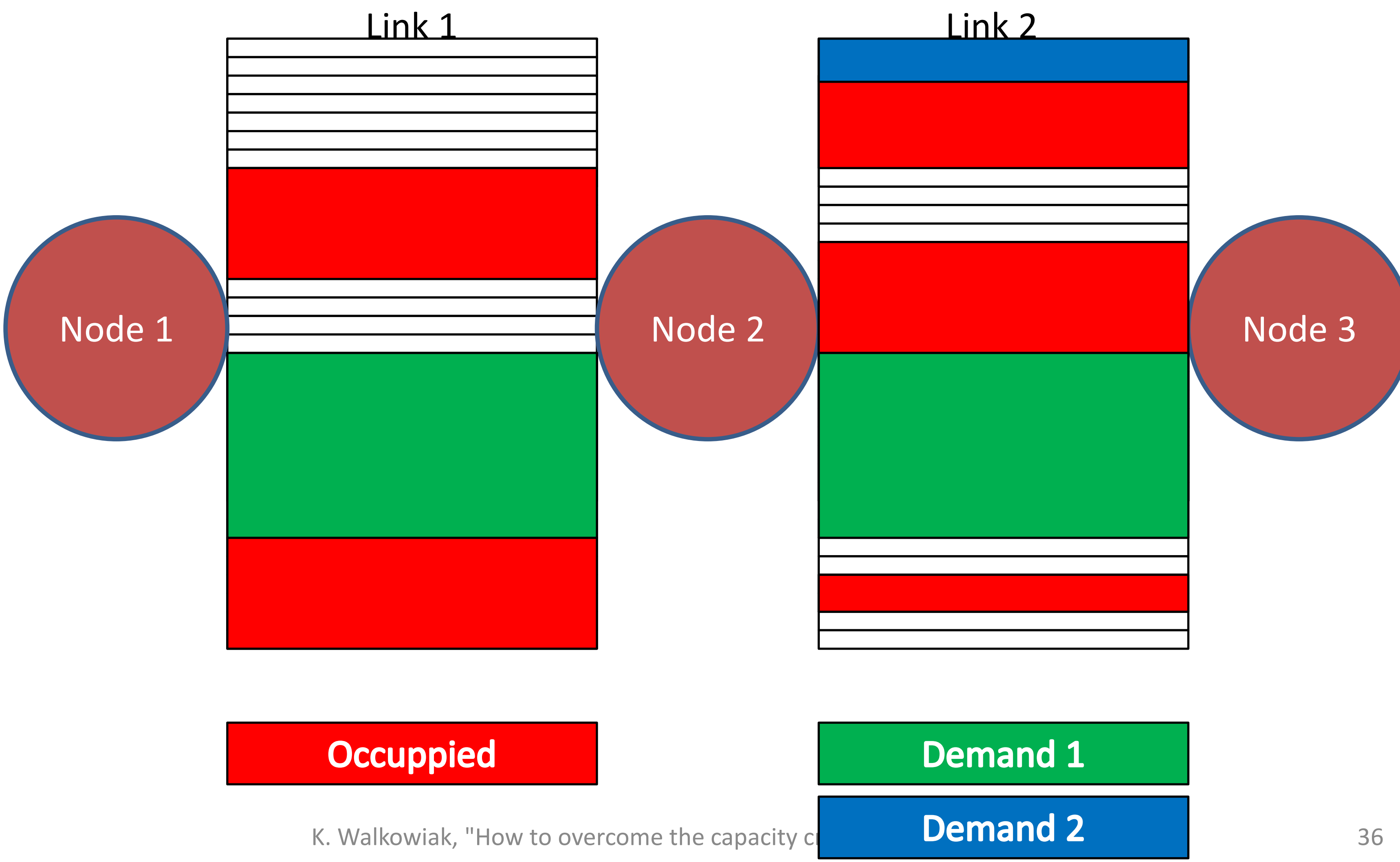
Fixed grid (WDM) vs flex grid (EON)



WDM Capacity Modeling



EON Capacity Modeling



Key Advantages of EONs

- Provisioning of bit-rates **beyond 100 Gb/s up to 1 Tb/s**
- **Increase of fiber capacity** through:
  - More effective use of optical spectrum (finer granularity)
  - Support of various modulation formats
  - Distance-adaptive transmission
- New survivability approach called **bandwidth squeezing**
- EONs can use **existing fibers**

Distance-Adaptive Transmission

- In EONs, it is possible to use **various modulation formats**, e.g., BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM, 64-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. All available modulation formats are examined and the most effective modulation format is selected, for which the considered transmission distance does not exceed the modulation transmission range

DAT - Example

Distance-Adaptive Modulation Formats for Bit-Rate 200 Gb/s

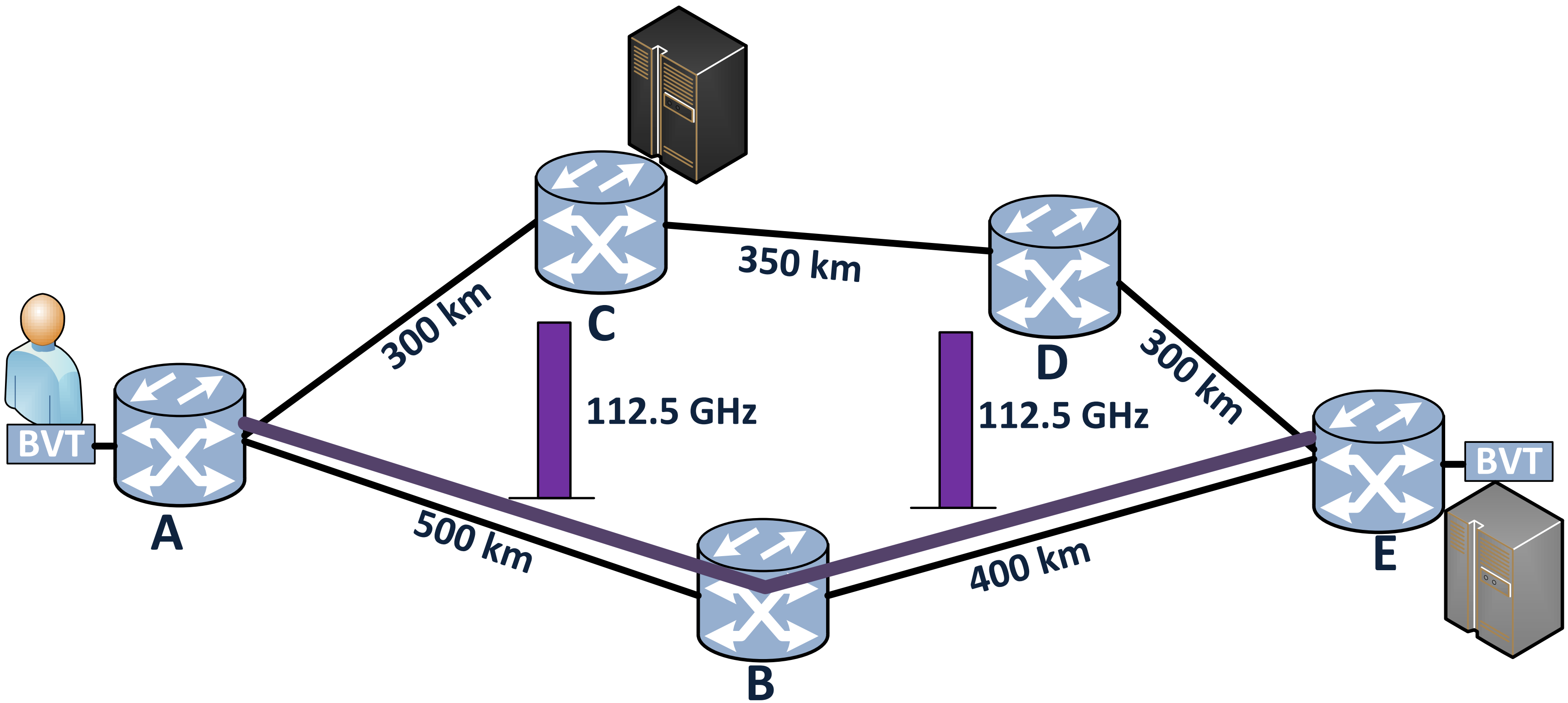
[C. Politi et al., "Dynamic Operation of Flexi-Grid OFDM-based Networks", OFC 2012]

	BPSK	QPSK	8-QAM	16-QAM	32-QAM	64-QAM
# slices	18	10	8	6	6	6
Range [km]	1912	1618	1325	1031	738	444

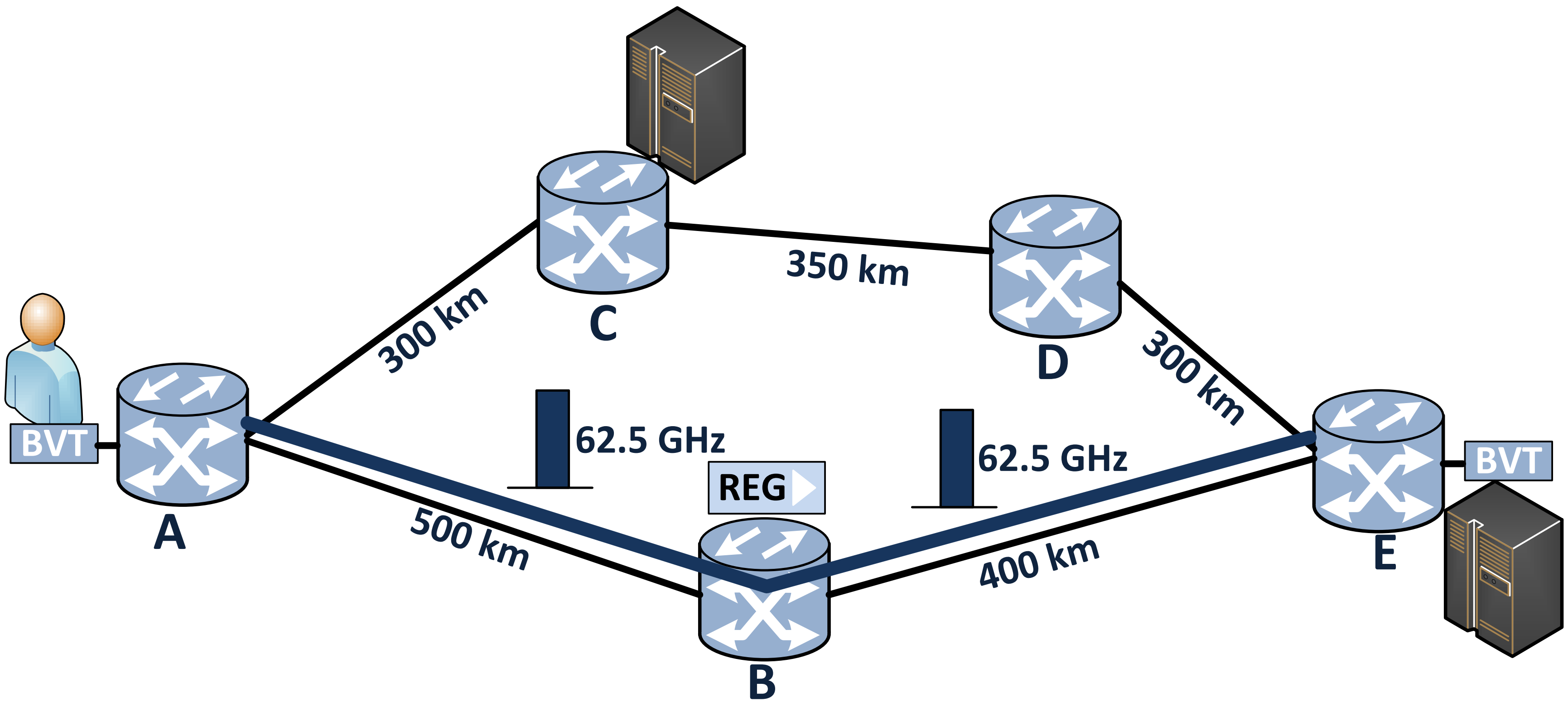
Path (tree) length 1200 km -> 8-QAM

Path (tree) length 1500 km -> QPSK

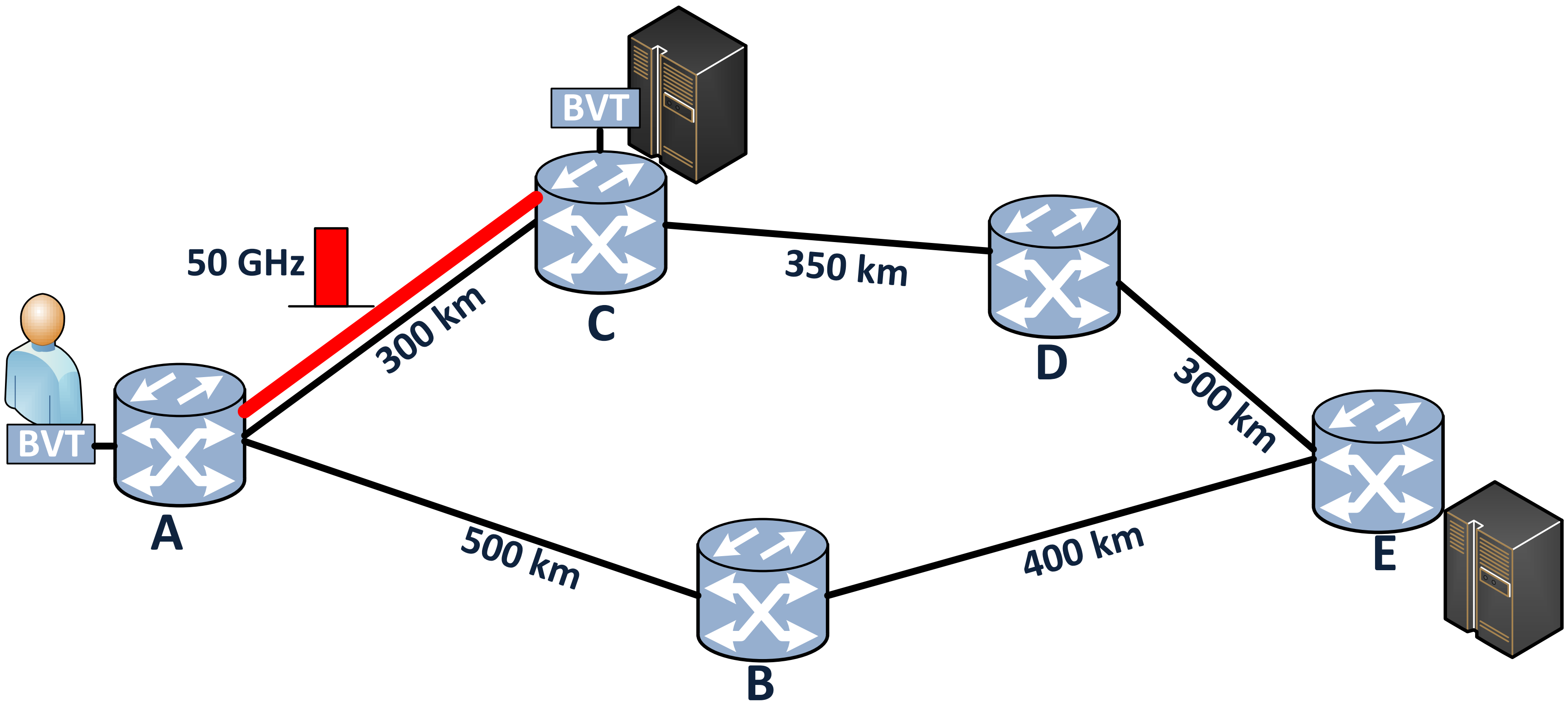
Example of DAT: QPSK



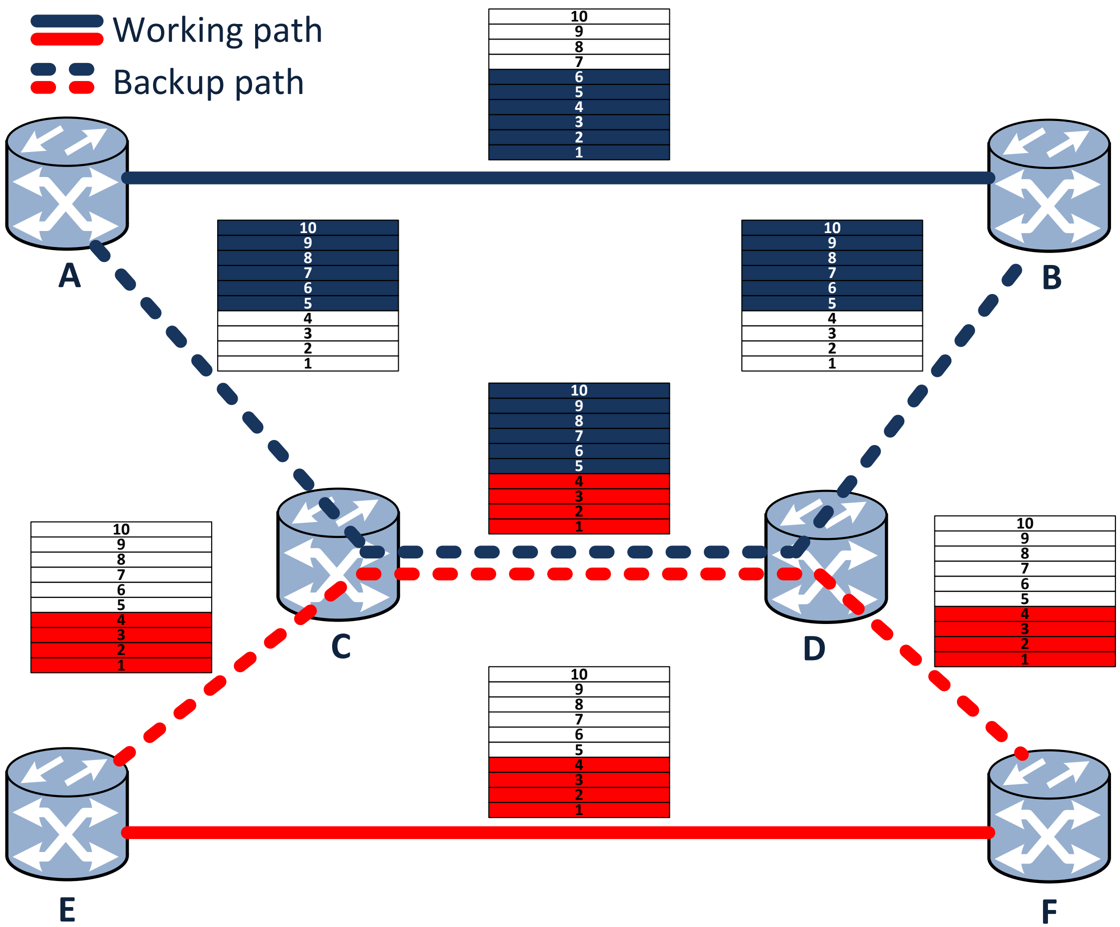
Example of DAT: 32-QAM



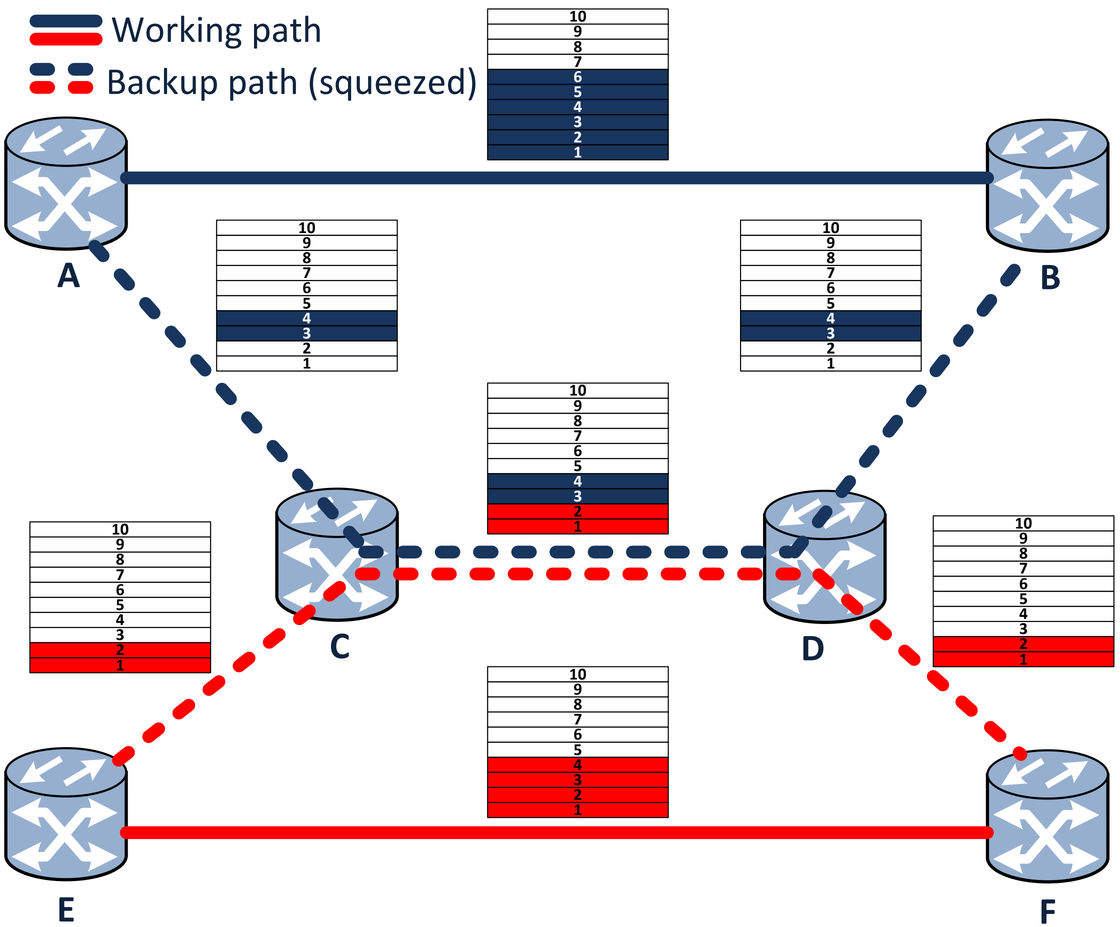
Example of DAT: 64-QAM



Dedicated Path Protection in EONs



Bandwidth squeezing

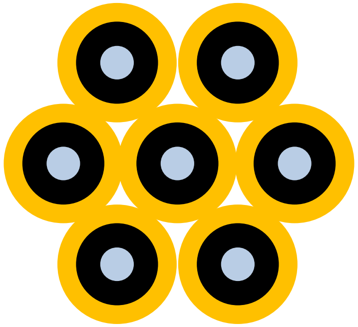


Space Dimension

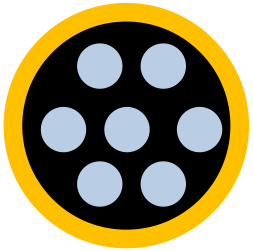
- Optical networks with **spatial flexibility** is a novel approach to optical networks that can be used to overcome the capacity crunch
- The key idea behind this approach is to use the **space domain**, in which the spatial resources can be flexibly assigned to different traffic demands
- The space dimension in fibers allows to use **space-division multiplexing (SDM)**
- 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

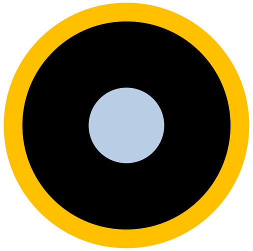
- **Fiber bundle** – standard fibers, often deployed in bundles (to offset the costs of digging trenches)



- **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



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Optimization Methods

- Linear Programming, e.g., Branch and Bound Algorithms
- Mathematical oriented methods (e.g., Kuhn-Tucker Conditions, Lagrangean relaxation)
- Metaheuristics (computational intelligence)
  - Genetic algorithm
  - Tabu Search (TS)
  - Simulated Annealing (SA)
  - …

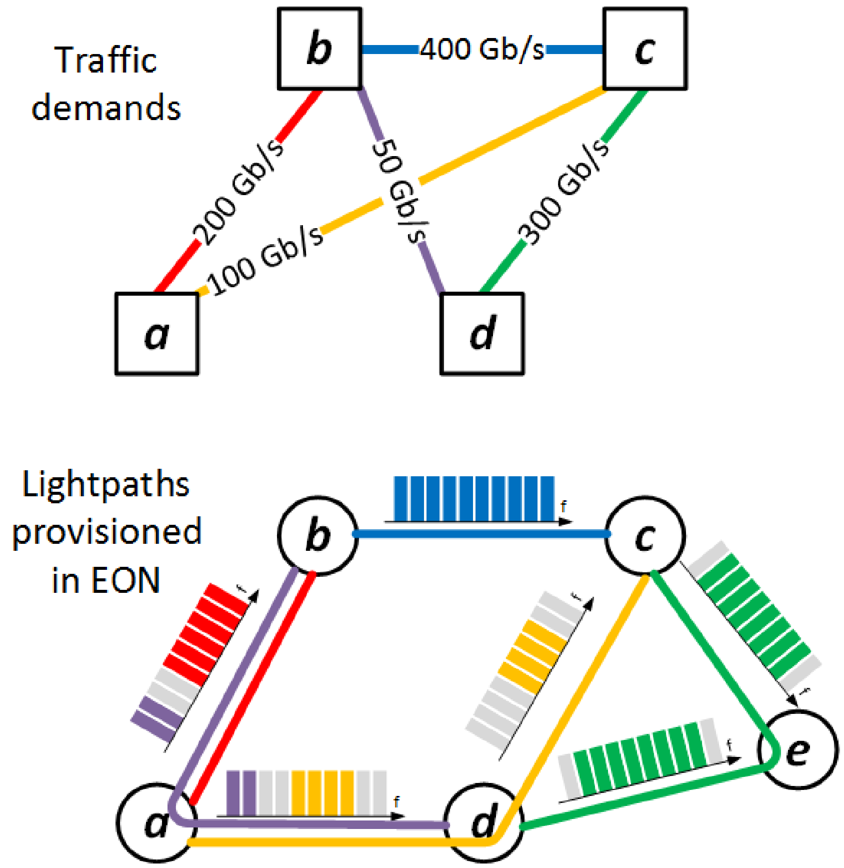
Notation

- The EON considered here is modeled as a **directed graph** ***G*=(*V*,*E*)** where ***V*** is a set of network nodes and ***E*** is a set of fiber links that connect pairs of network nodes
- On each network link $e \in E$, available spectrum resources are divided into **frequency slices** included in **set *S***
- By grouping a number of frequency slices $s \in S$, **optical channels** of different width can be created
- **Demands** (of various types) are included in **set *D***
- The link-path notation is used and a **set of candidate paths *P*(*d*)** is given for each demand $d \in D$
- Each demand *d* is described by **bit-rate** $\boldsymbol{h_d}$

Routing and Spectrum Allocation (RSA)

RSA 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)**

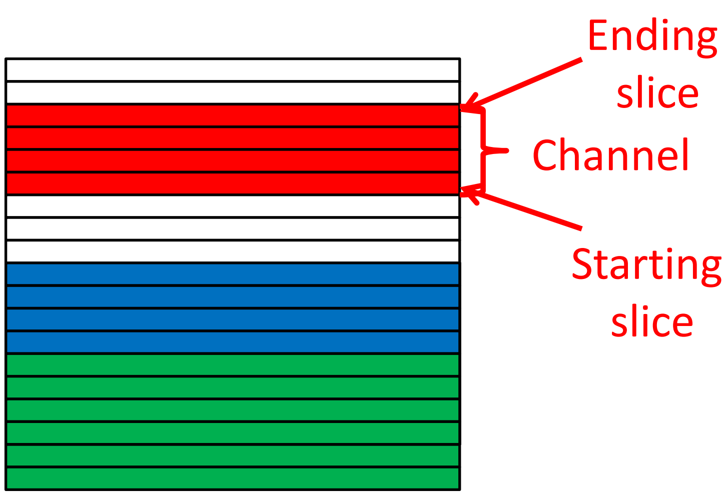


Demand Volume -> Number of Slices

- For each demand *d* the **requested volume** $\boldsymbol{h_d}$ is given in Gbps
- Let $\boldsymbol{n_{dp}}$ denote the **requested number of slices** for demand *d* on path *p*
- Value $\boldsymbol{n_{dp}}$ is calculated according to the **demand volume** h_d and the **modulation format** selected according to the path length

Spectrum Usage Modeling

- The main challenge in mathematical modeling of EONs in the RSA problem is the **contiguity constraint**, i.e., the ILP model of the RSA problem must ensure that slices assigned to a particular demand are adjacent (contiguous).
- Two approaches proposed in the literature to cope with this issue are:
  - **Slice-based** approach
  - **Channel-based** approach



Slice-Based Modeling (1)

- To denote **selection of a routing path**, the slice-based approach uses the binary variable $\boldsymbol{x_{dp}}$ which is 1 if candidate path $p \in P(d)$ is used to realize demand d and 0 otherwise
- To ensure that precisely **one routing path is selected** for each demand, the following constraint is used in slice-based modeling:

$$\sum_{p \in P(d)} x_{dp} = 1 \qquad d \in D$$

- Using variable x_{dp} it is easy to calculate **links that are used by demand *d*** according to the selected path p. To this end, let binary variable $\boldsymbol{y_{ed}}$ denote whether demand d uses link e:

$$\delta_{edp} x_{dp} \leq y_{ed} \qquad d \in D,\ p \in P(d)$$

Slice-Based Modeling (2)

- The main idea behind slice-based modeling is to **directly define spectrum slices** assigned to each demand
- For each demand $d \in D$ the integer variable $\boldsymbol{w_d}$ denotes the starting slice used for demand d and the integer variable $\boldsymbol{y_d}$ indicates the ending slice used for demand d
- Since variables w_d and y_d are defined regardless of particular network links, the **continuity constraint** is guaranteed
- To ensure the **contiguity constraint** resulting in all slices assigned to a particular demand being adjacent, the following inequality must be satisfied:

$$y_d - w_d + 1 \geq \sum_{p \in P(d)} x_{dp} n_{dp} \qquad d \in D$$

Slice-Based Modeling (3)

- To **avoid spectrum overlapping**, an additional variable is required, let $\boldsymbol{o_{di}}$ be 1 if the starting slice of demand *d* is smaller than that of demand *i* and 0 otherwise
- Since only one of the demands *d* and *i* can use the **smaller starting slice**, the following equality holds:

$$o_{di} + o_{id} = 1 \qquad d,i \in D: d \neq i$$

- However, not all pairs of demands need to be controlled against spectrum overlapping. Thus, the binary variable $\boldsymbol{c_{di}}$ is used to denote whether demands *d* and *i* use **common link**(s):

$$c_{di} \geq y_{ed} + y_{ei} - 1 \qquad e \in E,\ d,i \in D: d \neq i$$

Slice-Based Modeling (4)

- To guarantee the **non-overlapping constraint**, which states that a slice on a particular link can be allocated to at most one demand, two additional constraints are needed:

$$y_i - w_d + 1 \leq |S|(1 + o_{di} - c_{di}) \quad d,i \in D: d \neq i$$

$$y_d - w_i + 1 \leq |S|(2 - o_{di} - c_{di}) \quad d,i \in D: d \neq i$$

- The **first constraint is only active** if both demands *d* and *i* share at least one link (c_{di} = 1) and the starting slice of demand *d* is larger or equal than that of demand *i* (o_{di} = 0), then $y_i + 1 \leq w_d$
- The **second constraint is activated** only if both demands *d* and *i* use a common link (c_{di} = 1) and the starting slice of *d* is smaller than of *i* (o_{di} = 1), then $y_d + 1 \leq w_i$

Slice-Based Modeling (5)

variables

x_{dp} = 1, if candidate path *p* is used to realize demand *d*; 0, otherwise (binary)

y_{ed} = 1, if demand *d* uses link *e*; 0, otherwise (binary)

o_{di} = 1, if the starting slice of demand *d* is smaller than that of demand *i*; 0, otherwise (binary)

c_{di} = 1, if demands *d* and *i* use common link(s); 0, otherwise (binary)

w_d indicates the starting slice used for demand d (integer)

y_d indicates the ending slice used for demand *d* (integer)

constraints

$\sum_{p \in P(d)} x_{dp} = 1 \qquad d \in D$

$\delta_{edp} x_{dp} \leq y_{ed} \qquad d \in D,\ p \in P(d)$

$y_d - w_d + 1 \geq \sum_{p \in P(d)} x_{dp} n_{dp} \qquad d \in D$

$o_{di} + o_{id} = 1 \qquad d,i \in D: d \neq i$

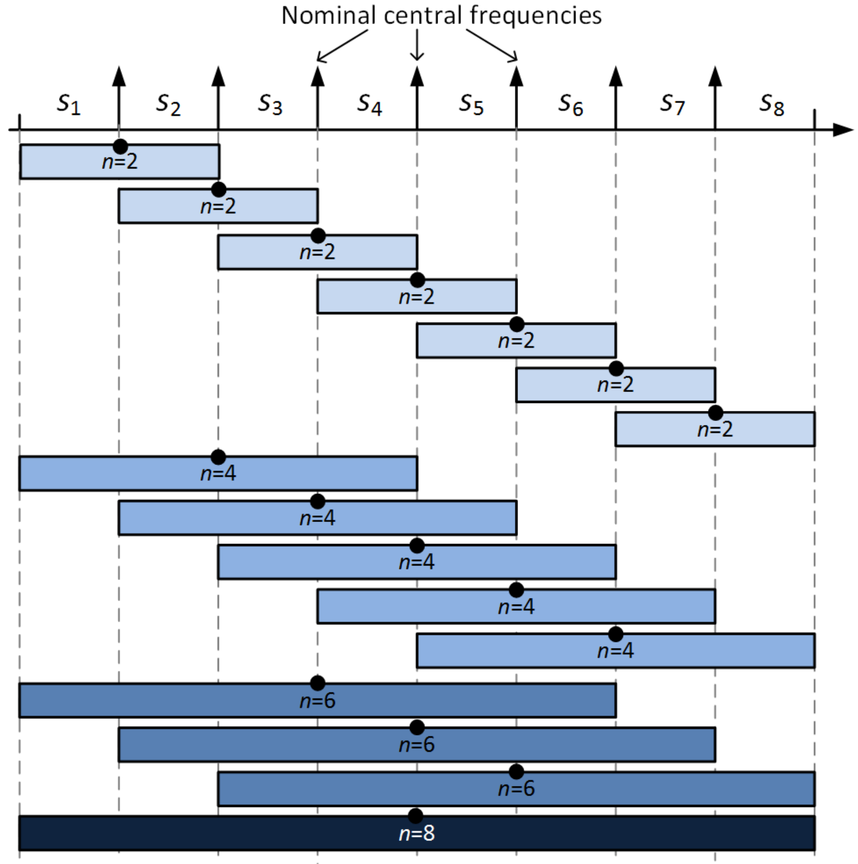
$c_{di} \geq y_{ed} + y_{ei} - 1 \qquad e \in E,\ d,i \in D: d \neq i$

$y_i - w_d + 1 \leq |S|(1 + o_{di} - c_{di}) \quad d,i \in D: d \neq i$

$y_d - w_i + 1 \leq |S|(2 - o_{di} - c_{di}) \quad d,i \in D: d \neq i$

Channel-Based Modeling (1)

- A ***channel*** can be defined as a pre-computed **set of contiguous slices** of a particular size (number of slices)
- For **eight slices available** in the network, there are:
  - **7 channels** with a size of **two slices**
  - **5 channels** with a size of **four slices**
  - **3 channels** with a size of **six slices**
  - **1 channel** with a size of **eight slices**



[L. Velasco, M. Klinkowski, M. Ruiz, and J. Comellas, Modeling the routing and spectrum allocation problem for flexgrid optical networks. Photnic Network Communications, Vol. 24, No. 3, pp. 177–186, 2012]

Channel-Based Modeling (2)

- Let $\boldsymbol{C_n}$ denote a set of all channels with a size of *n* slices
- Due to the DAT rule, it is possible that the same demand *d* can require **different numbers of slices** depending on the routing path selected to realize the demand
- Let $\boldsymbol{C(d,p)}$ be a set of candidate channels for demand *d* using path *p*
- Constant $\boldsymbol{\gamma_{dpcs}}$ defines if slice *s* is included in set $c \in C(d,p)$, i.e., γ_{dpcs} is 1, if channel *c* associated with demand *d* on path *p* uses slice *s,* and 0 otherwise

Channel-Based Modeling (3)

- To **combine the routing and spectrum (channel) allocation** in a one decision variable, let $\boldsymbol{x_{dpc}}$ denote a binary variable which is 1 if channel *c* on candidate path *p* is used to realize demand *d* and 0 otherwise
- To satisfy **continuity and contiguity constraints** for each demand $d \in D$ only one path and one channel can be selected, i.e., the following equality must be satisfied:

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

- To **avoid spectrum overlapping** the following constraint is formulated:

$$\sum_{d \in D} \sum_{p \in P(d)} \sum_{c \in C(d,p)} \gamma_{dpcs} \delta_{edp} x_{dpc} \leq 1 \quad e \in E \quad s \in S$$

Channel-Based Modeling (4)

sets (additional)

S slices

$C(d,p)$ candidate channels for demand d on path p

constants

γ_{dpcs} = 1, if channel c of demand d on path p uses slice s; 0, otherwise

variables

x_{dpc} = 1, if channel c on path p is used for demand d; 0, otherwise (binary)

constraints

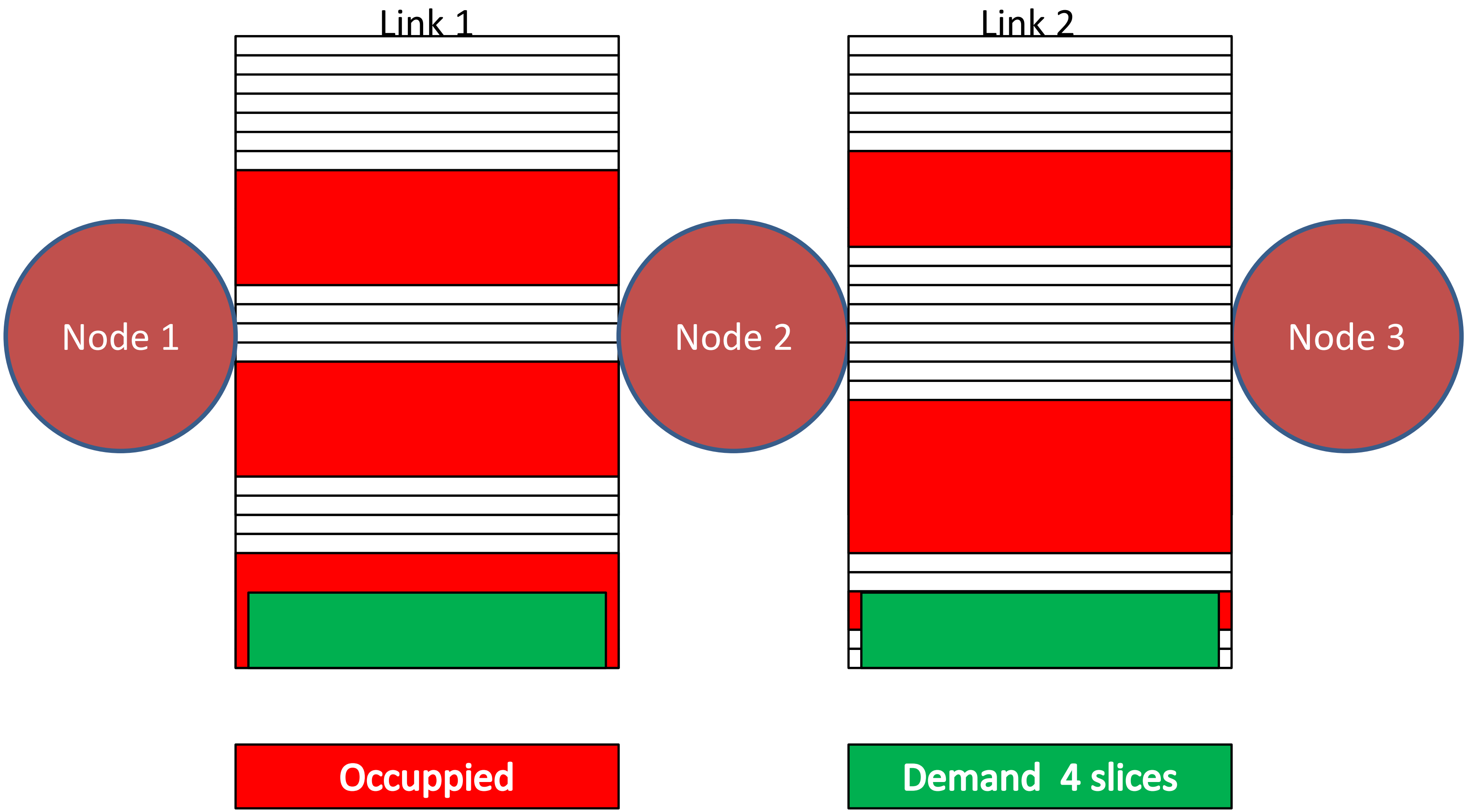
$\sum_{p \in P(d)} \sum_{c \in C(d,p)} x_{dpc} = 1$ $\quad d \in D$

$\sum_{d \in D} \sum_{p \in P(d)} \sum_{c \in C(d,p)} \gamma_{dpcs} \delta_{edp} x_{dpc} \leq 1$ $\quad e \in E \quad s \in S$

First Fit – Spectrum Allocation (1)

- A **subproblem** of the RSA is **spectrum allocation** problem, i.e., to find spectrum window for a given routing path
- A **common approach** to solve this problem is the **First Fit** (**FF_Spectrum**) approach
- The idea is to find **a free spectrum window** (range of adjacent slices) that allows to allocate the demand on all links included in the routing path with the **lowest value of the maximum slice index** used in the window

First Fit – Spectrum Allocation (2)



Greedy Algorithms

- **First Fit (FF):**

1. allocate the demand on the shortest routing path using the FF_Spectrum for spectrum allocation

- **Longest Path First (LPF):**

1. Sort demands in a decreasing order of the shortest path length for a particular demand
2. Process the demands one by one and select a path among all candidate routing paths that provides the lowest slice index using the FF_Spectrum for spectrum allocation

- **Most Subcarriers First (MSF):**

1. Sort demands in a decreasing order of the requested number of slices

AFA Algorithm (1)

- The main idea of the AFA method is to **adaptively select a sequence of processed demands** in order to minimize objective function
- Demands are processed in sets created according to the **required number of slices**
- For each set, **all demands are tried to be allocated** to find the **best allocation** (with lowest slice index), next the allocated demand is removed from the set
- The algorithm was used in our previous papers:

  [Klinkowski M., Walkowiak K., Routing and Spectrum Assignment in Spectrum Sliced Elastic Optical Path Network, IEEE Communications Letters, Vol. 15., No. 8, 2011]

  [Walkowiak K., Klinkowski M., Joint Anycast and Unicast Routing for Elastic Optical Networks: Modeling and Optimization, ONS ICC 2013]

  [Klinkowski M., Walkowiak K., On Advantages of Elastic Optical Networks for Provisioning of Cloud Computing Traffic, IEEE Networks, Vol. 27, No. 6, 2013]

AFA Algorithm (2)

For each demand the minimum slice requirement is found:

- d=1: n_{11}=4, n_{12}=4, n_{13}=6 –> $\mathbf{n_1^{min}=4}$
- d=2: n_{21}=6, n_{22}=6, n_{23}=8 –> $\mathbf{n_2^{min}=6}$
- d=3: n_{31}=2, n_{32}=2, n_{33}=2 –> $\mathbf{n_3^{min}=2}$
- d=4: n_{41}=8, n_{42}=8, n_{43}=10 –> $\mathbf{n_4^{min}=8}$
- d=5: n_{51}=8, n_{52}=10, n_{53}=10 –> $\mathbf{n_5^{min}=8}$
- d=6: n_{61}=4, n_{62}=6, n_{63}=8 –> $\mathbf{n_6^{min}=4}$

Demands are processed in 4 sets:

- n^{min}=8 -> $\mathbf{D_8=\{4,5\}}$
- n^{min}=6 -> $\mathbf{D_6=\{2\}}$
- n^{min}=4 -> $\mathbf{D_4=\{1,6\}}$
- n^{min}=2 -> $\mathbf{D_2=\{3\}}$

Computational Intelligence

- Computational intelligence are **metahueristic algorithms** combining various approaches mostly observed in the **nature**
- Computational intelligence methods are mostly **stochastic**, since they use some random elements
- Computational intelligence algorithms yield **suboptimal results** without the optimality guarantee
- Computational intelligence algorithms solve a discrete problem

$$\min F(x) \quad x \in S$$

where ***S*** **is a finite space of feasible solutions**

- The original computational intelligence werede designed for problems **without constraints**

Problem Encoding for RSA (1)

- A key issue in metaheuristic algorithms is **encoding** of the problem
- In the RSA, for each demand a **path *p*** and **channel *c*** (spectrum) must be selected
- First possible encoding is as follows:

$$X=[(p_1,c_1),(p_2,c_2),\ldots,(p_{|D|},c_{|D|})]$$

- However, using this encoding it is **very hard to define moves or operations** that ensures the obtained solution is feasible
- A **number of feasible solutions in the RSA problem is very small**
- Usually a very **small modification** of a feasible solution with this encoding creates a **non-feasible solution**

Problem Encoding for RSA (2)

- Let $\boldsymbol{seq_d}$ denote a **sequence number of demand *d***, i.e., the demads are processed according to a particular ordering
- Another possible encoding is as follows:

$$\boldsymbol{X=[(p_1,seq_1),(p_2,seq_2),\ldots,(p_{|D|},seq_{|D|})]}$$

- To find a solution and objective function, demands are allocated according to the **sequence $\boldsymbol{seq_d}$ on path $\boldsymbol{p_d}$** and using the **FF_Spectrum** for spectrum allocation
- This approach **ensures** that the solution *X* is **always feasible**

Problem Encoding for RSA (3)

- The last encoding is as follows:

$$X=[seq_1, seq_2,\ldots,seq_{|D|}]$$

- To find a **solution and objective function**, demands are allocated according to the sequence seq_d, path and spectrum are determined using a greedy procedure as in MSF, LPF and AFA methods
- This approach **ensures** that the solution X is **always feasible**

Tabu Search for RSA

- Encoding $\boldsymbol{X=[(p_1,seq_1),(p_2,seq_2),\ldots, (p_{|D|},seq_{|D|})]}$
- The first step is to prepare **initial solution** using other heuristic method, e.g. AFA
- TS algorithm **iteratively searches** through the solution space for better solution by applying move operation to the current solution
- Search process is controlled by **memory mechanisms**: list of tabu moves and diversification process
- The **stop condition** depends on maximum number of iterations and limited processing time

[Walkowiak K., Klinkowski M., Rabiega B., Goścień R., Routing and Spectrum Allocation Algorithms for Elastic Optical Networks with Dedicated Path Protection, Optical Switching and Networking, 2014, **Fabio Neri Award**]

TS Move – Order Swap

Current Solution: Allocation Order											
D10	D 2	D 5	D 9	D 3	**D 6**	D12	D 8	D 4	D 1	**D11**	D 7

Tabu Move – Demands Order Swap: (D6, D11)

Candidate Solution: Allocation Order											
D10	D 2	D 5	D 9	D 3	**D11**	D12	D 8	D 4	D 1	**D 6**	D 7

TS Move – Path Swap

Current Solution: Path Allocation Scheme

D10 p=1	D 2 p=3	D 5 p=1	D 9 p=2	D 3 p=1	D6 p=2	D12 p=1	D 8 p=1	D 4 p=2	D 1 p=4	D6 p=1	D 7 p=2

Tabu Move – Path Swap: (D6, k=1)

Candidate Solution: Path Allocation Scheme

D10 p=1	D 2 p=3	D 5 p=1	D 9 p=2	D 3 p=1	D6 p=1	D12 p=1	D 8 p=1	D 4 p=2	D 1 p=4	D6 p=1	D 7 p=2

Simulated Annealing for RSA

- Encoding $\boldsymbol{X=[(p_1,seq_1),(p_2,seq_2),\dots,(p_{|D|},seq_{|D|})]}$
- The first step is to prepare **initial solution** using other heuristic method, e.g. AFA
- To generate a neighbor of the current state (solution *X*), **two randomly selected demands are swapped** in the sequence (the same as in the TS) and thus a new solution is generated

[Aibin M., Walkowiak K., Simulated Annealing Algorithm for Optimization of Elastic Optical Networks with Unicast and Anycast Traffic, 16th International Conference on Transparent Optical Networks ICTON 2014]

Comparison of Algorithms – Anycast and Unicast Flows

	CPLEX	FF	MSF	LSF	AFA	TS	SA
Average optimality gap							
NSF15	-	45.10%	13.10%	18.10%	7.80%	**2.70%**	3.80%
Euro16	-	48.60%	11.50%	14.30%	6.90%	**4.00%**	4.30%
Lengths of 95% confidence intervals							
NSF15	-	2.09%	1.51%	1.78%	1.20%	0.55%	0.69%
Euro16	-	2.15%	1.43%	1.56%	1.25%	0.68%	0.92%
Average execution time in seconds							
NSF15	256	<0.001	<0.001	<0.001	<0.001	7	75
Euro16	34	<0.001	<0.001	<0.001	<0.001	12	43

Average Gap to AFA - Anycast and Unicast Flows, Larger Networks

No. of Paths	Slices	FF	MSF	LSF	TS	SA
Network UBN24 with 40 Tbps traffic						
2	407	51.00%	5.70%	6.90%	-4.30%	**-4.90%**
3	336	56.60%	5.10%	5.20%	-4.30%	**-5.30%**
5	287	60.10%	3.00%	3.50%	-1.40%	**-2.90%**
10	277	62.70%	1.90%	3.00%	**-2.70%**	-2.10%
30	274	63.50%	2.00%	3.80%	-1.60%	**-2.60%**
Network Euro28 with 50 Tbps traffic						
2	455	50.50%	3.30%	3.90%	**-17.60%**	-6.40%
3	414	57.30%	2.40%	3.60%	-3.80%	**-5.00%**
5	392	58.80%	2.00%	3.10%	-3.30%	**-3.70%**
10	387	60.90%	1.90%	3.20%	**-4.20%**	-2.90%
30	384	63.90%	2.60%	4.10%	-3.10%	**-3.70%**

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- Introduction
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- **Case Study**
- Conclusions

Case Study - Assumptions

- Location of **data center** nodes and **interconnection** points was made according to data available at http://www.datacentermap.com/
- A model of service demands is created for period **2012-2020** under the forecast of **Cisco** reports. The traffic matrix in each network includes A-Z service demands of four types:
  - **City – City (CC)** traffic represents all non data center traffic calculated with CAGR 18%
  - **City – Data Center (CD)** traffic represents all data center to user traffic calculated with CAGR 31%
  - **Data Center – Data Center (DD)** traffic calculated with CAGR 32%
  - **International (IN) traffic** – all traffic leaving/entering the particular network calculated as a percentage of all network traffic
- Multivariable **gravity model** is used to generate demands

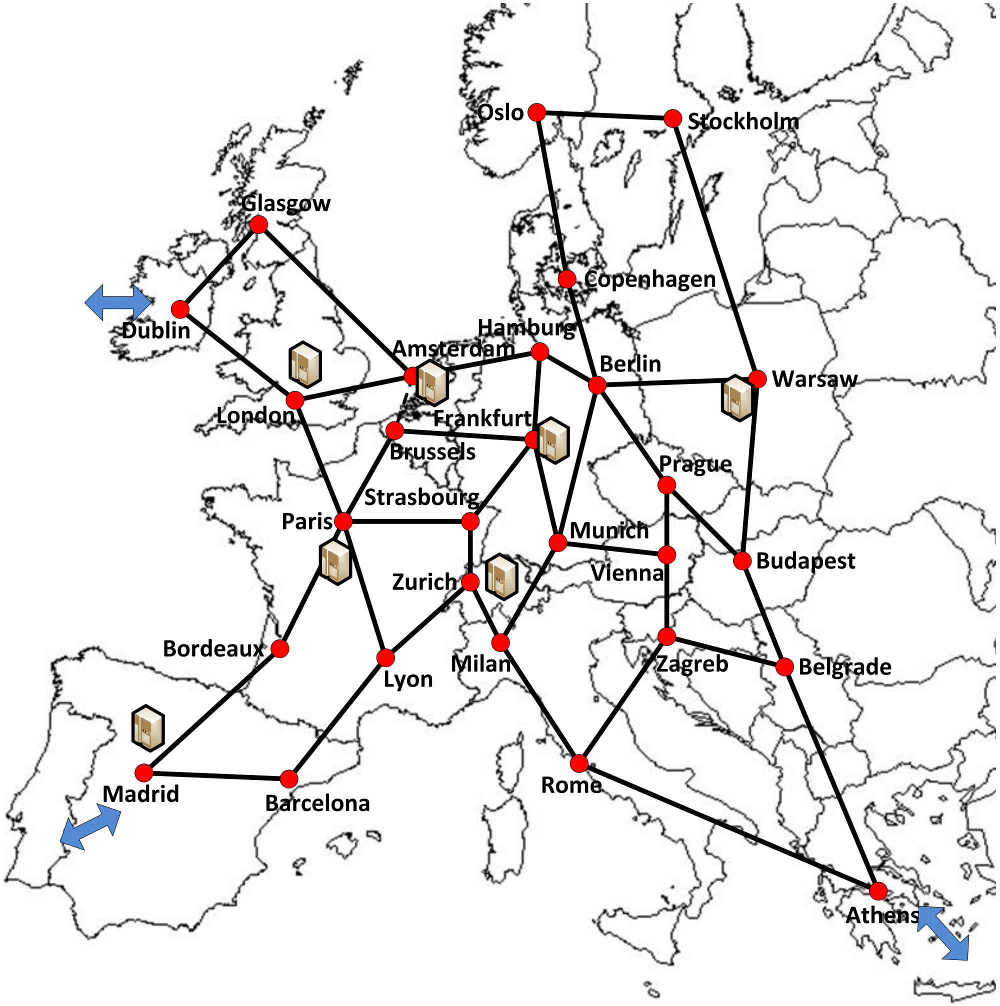
[Klinkowski M., Walkowiak K., On Advantages of Elastic Optical Networks for Provisioning of Cloud Computing Traffic, IEEE Network, Vol. 27, No. 6, 2013]

[Goścień R., Walkowiak K., Klinkowski M., Rak J., Protection in Elastic Optical Networks, IEEE Network, Vol. 29, No. 6, 2015]

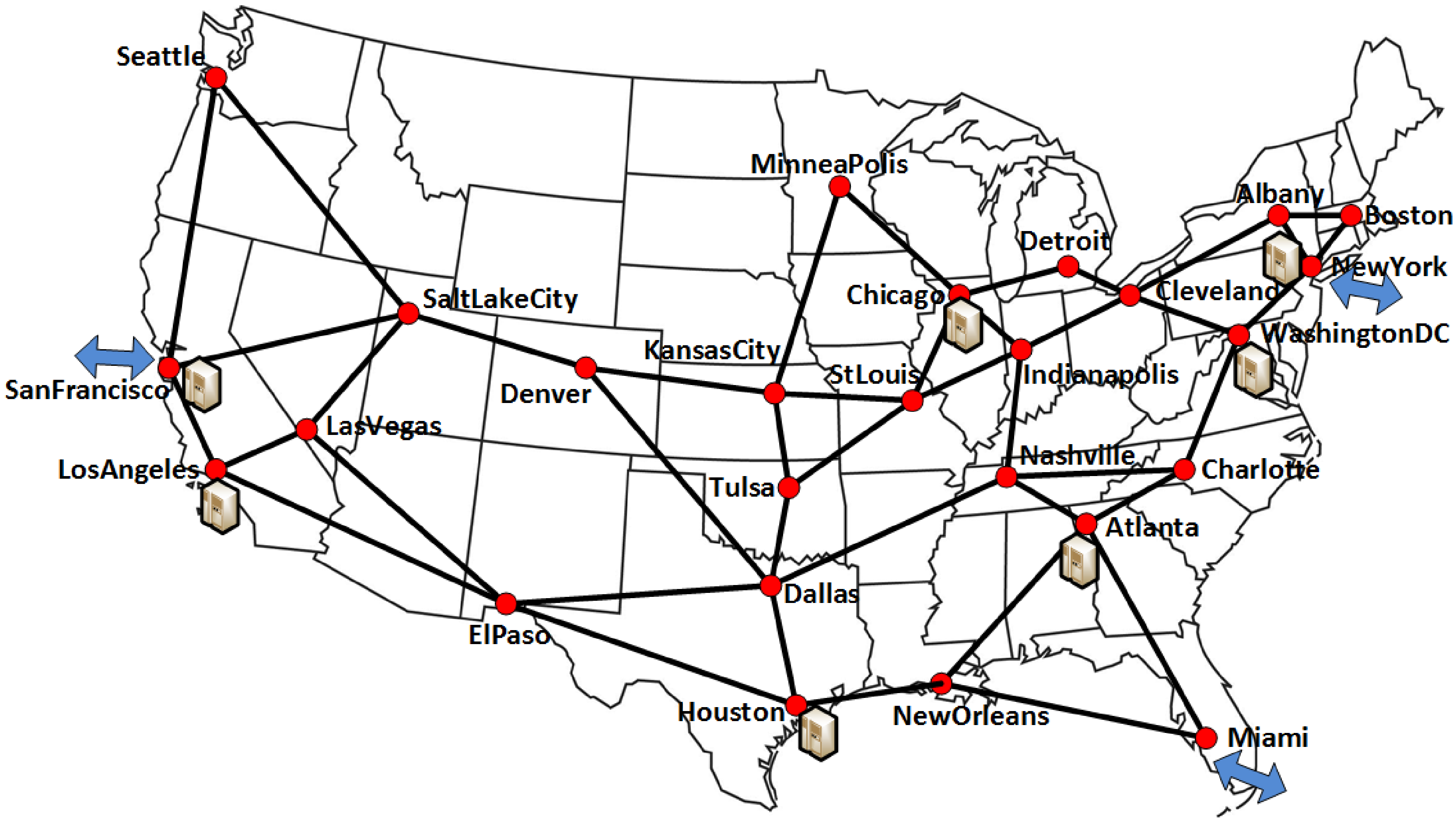
Traffic

Euro Network					
Year	Traffic Volume [Tb/s]				
	City-City	City-Data Center	Data Center – Data Center	International	Total
2012	2.1	10.0	4.0	4.0	20.1
2014	2.9	17.1	6.9	6.7	33.6
2016	4.1	29.3	12.0	11.3	56.7
2018	5.6	50.3	20.9	19.2	96.1
2020	7.9	86.3	36.5	32.7	163.3
US Network					
Year	Traffic Volume [Tb/s]				
	City-City	City-Data Center	Data Center – Data Center	International	Total
2012	3.5	16.8	6.7	3.0	30.0
2014	4.9	28.8	11.6	5.0	50.4
2016	6.8	49.5	20.3	8.5	85.1
2018	9.5	84.9	35.3	14.4	144.1
2020	13.3	145.6	61.5	24.5	244.9

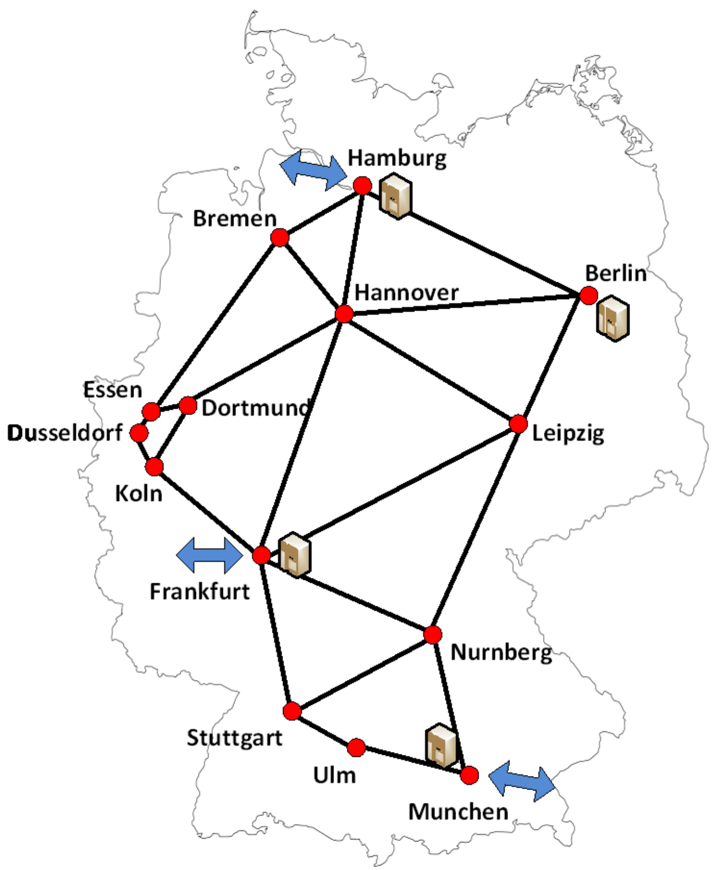
Euro28 Network



US26 Network



DT14 Network

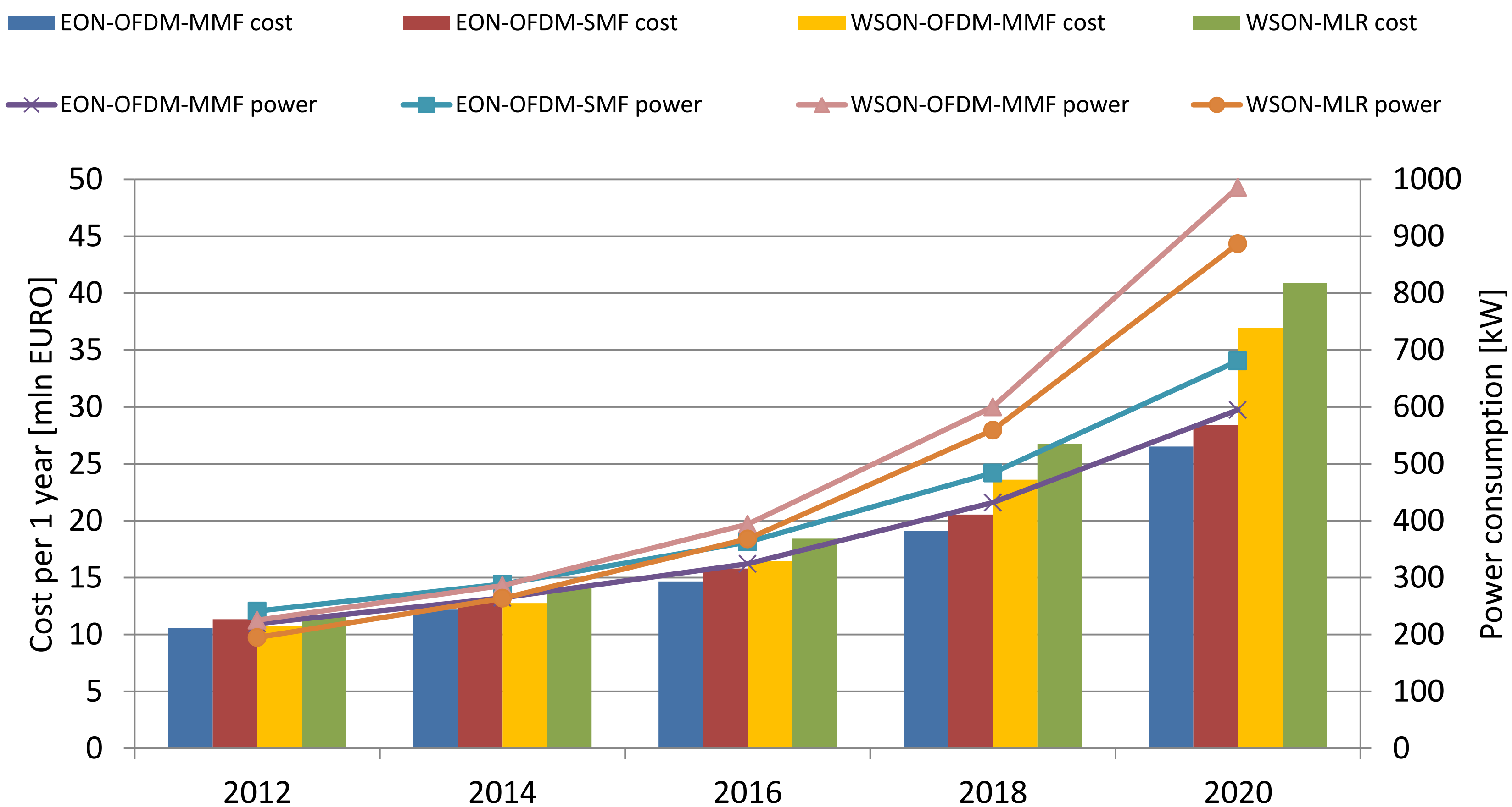


Optical Scenarios

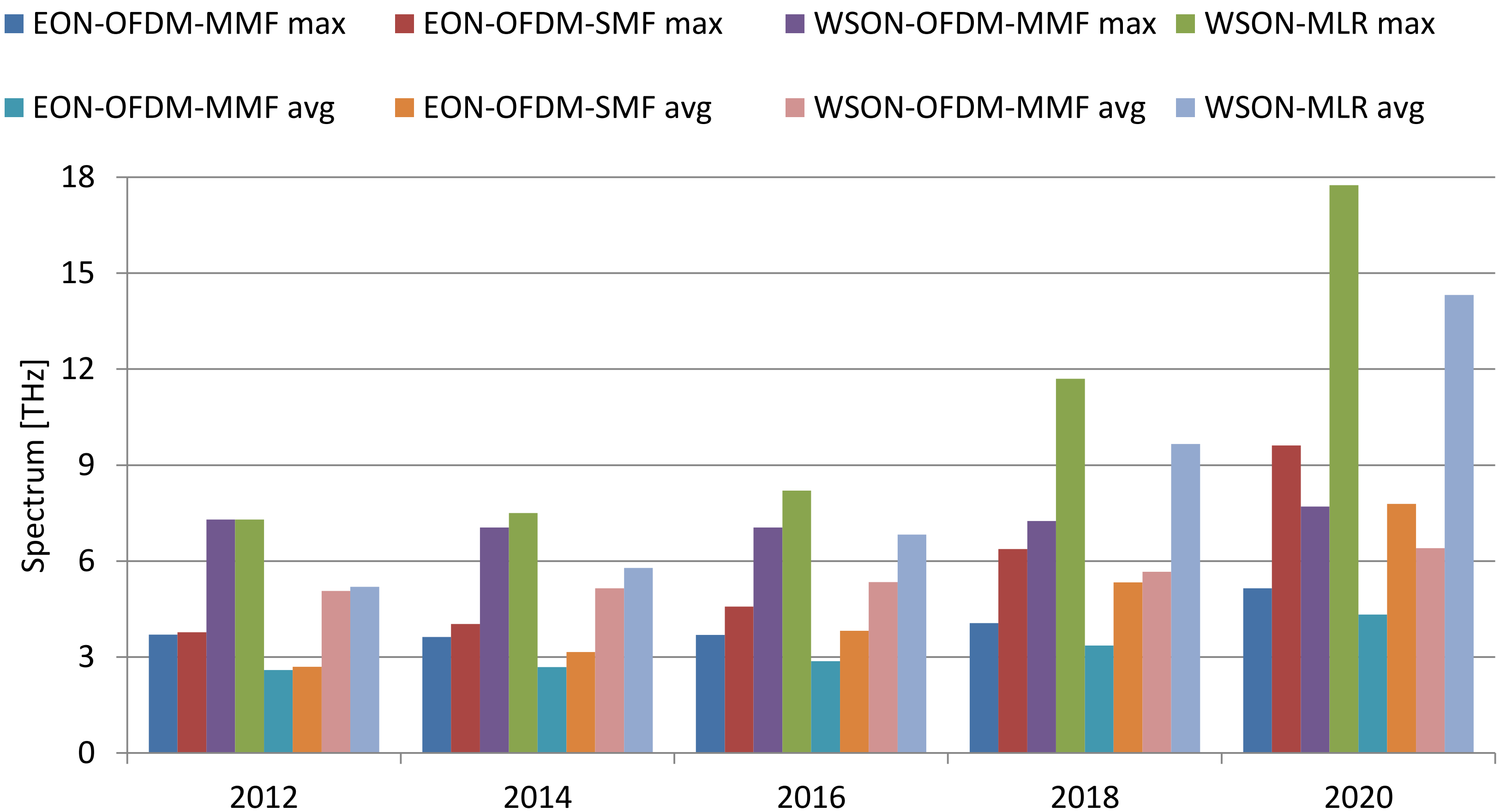
- **WSON-MLR** - a WDM network allowing for multi-line-rate transmission with fixed 10 Gbps, 40 Gbps, and 100 Gbps WDM transponders and the transmission distance limits equal to, respectively, 3200 km, 2300 km, and 2100 km
- **WSON-OFDM-MMF** – WDM with BV-Ts as in EON
- **EON-OFDM-SMF** - an elastic optical network with BV-Ts implementing the PDM-OFDM technology and the QPSK modulation format
- **EON-OFDM-MMF** - an elastic optical network with software-defined BV-Ts implementing the PDM-OFDM technology and modulation formats selected adaptively between BPSK, QPSK, and m-QAM, where *m* belongs to {8, 16, 32, 64}; here, the spectral efficiency is equal to 1,2,... ,6, respectively, for these modulation formats

We make use of the transmission model presented in [C. Politi, V. Anagnostopoulos, C. Matrakidis, A. Stavdas, A. Lord, V. Lopez, and J.P. Fernandez-Palacios, "Dynamic Operation of Flexi-Grid OFDM-based Networks", in *Proceedings of OFC*, Los Angeles, USA, 2012], which estimates the transmission distance in a function of the selected modulation level and transported bit-rate

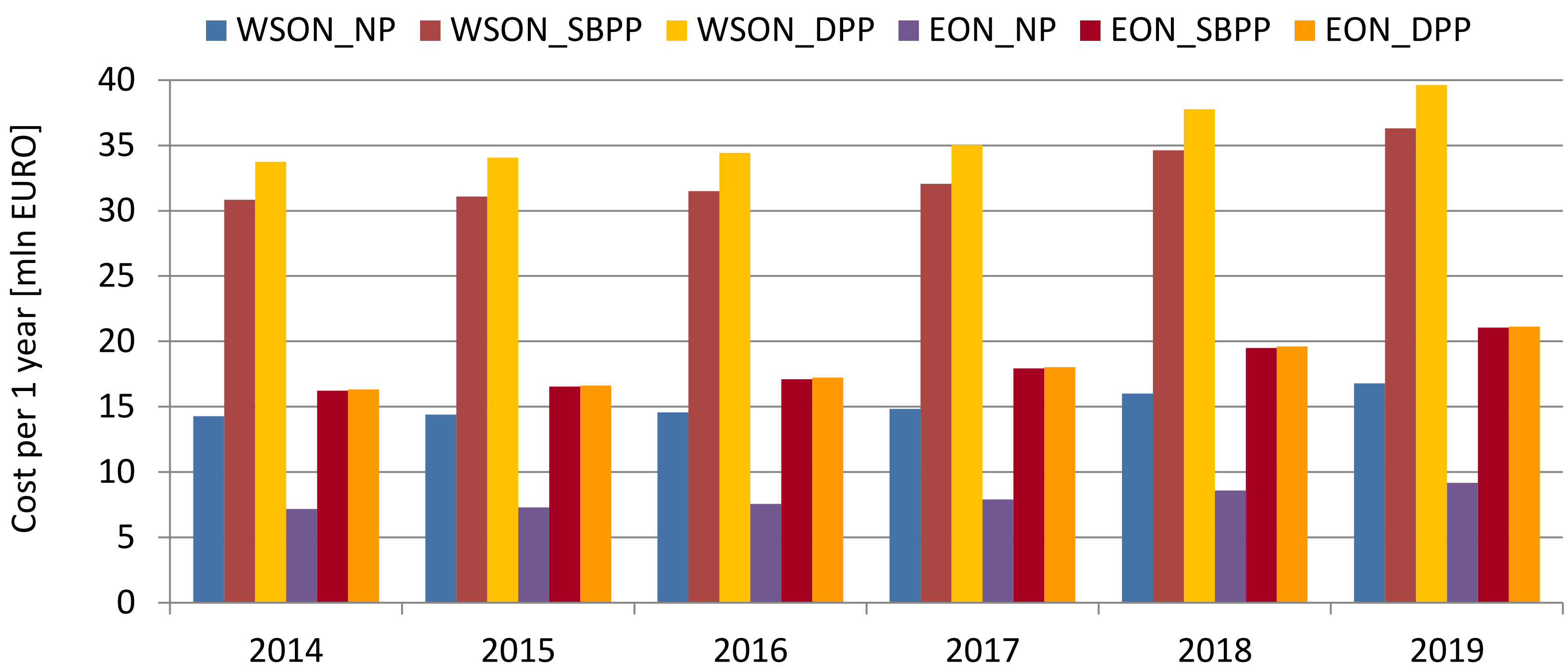
Cost and Power Consumption – US26



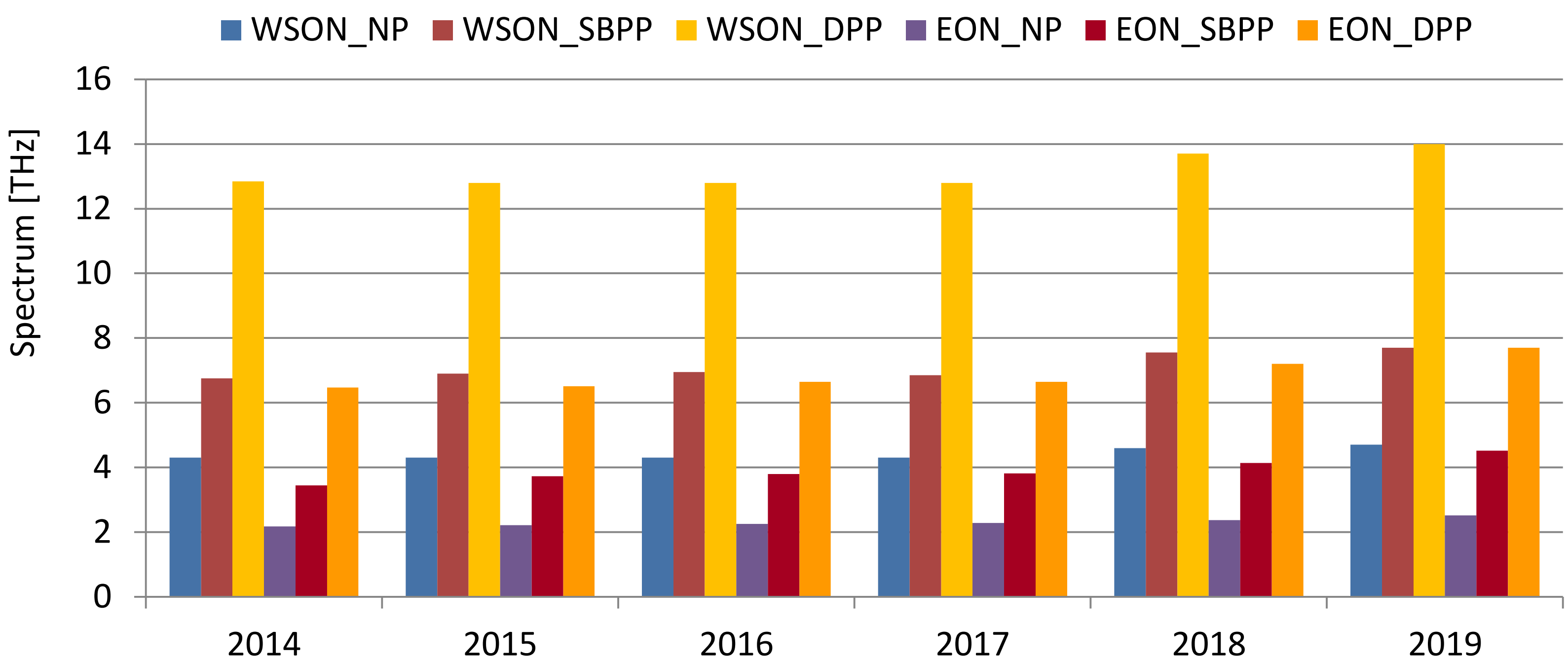
Spectrum Usage – US26



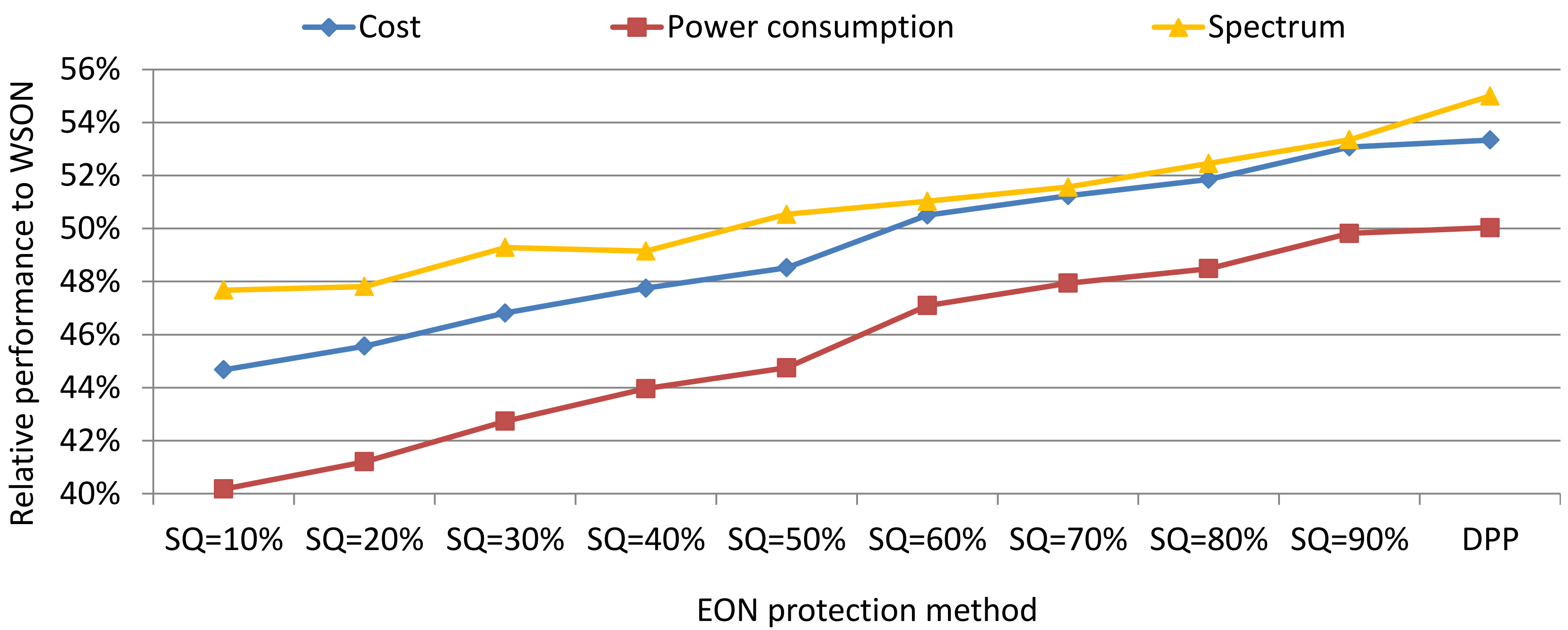
Protection in EON and WSON Cost for Euro28



Protection in EON and WSON Spectrum Usage for Euro28



Squeezed Protection for Euro28



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Conclusions

- **New optical technologies** for transport networks are required **to overcome** the possible future **capacity crunch**
- The currently used **WDM** technology will be probably replaced by the **Elastic Optical Network** approach in near future and **Space-Division Multiplexing** technology in more distant future
- Optimization of EONs is **very challenging** due to a very large solution space and very small number of feasible solutions
- **ILP modeling** works only for **small problem instances**, therefore effective heuristics are needed
- **SDM** technology triggers many **new optimization problems even more difficult than in EONs** and thus **new algorithms** are required to provide the solutions

Thank you for attention

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