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Design and Re-optimization Algorithms for Elastic Optical Networks

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Outline

- I. RSA Basics**
- II. Network Design**
- III. RSA under Dynamic Traffic**
- IV. Extending networks life-cycle**
- V. Towards Cognitive Networking**



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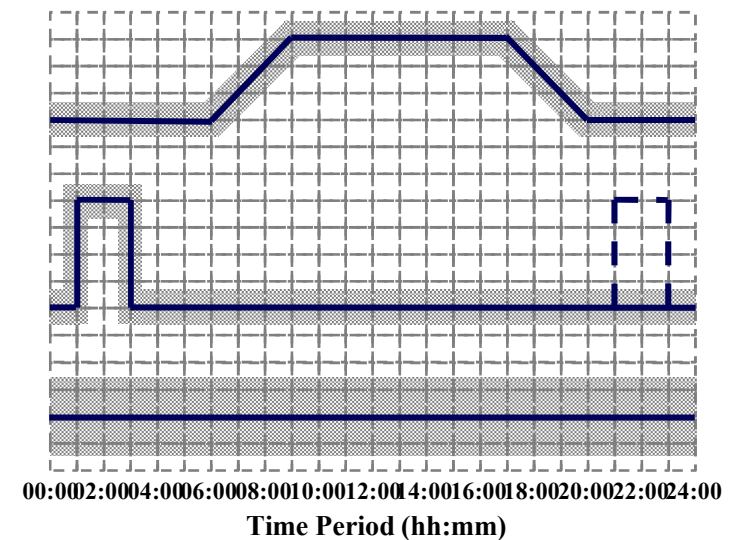
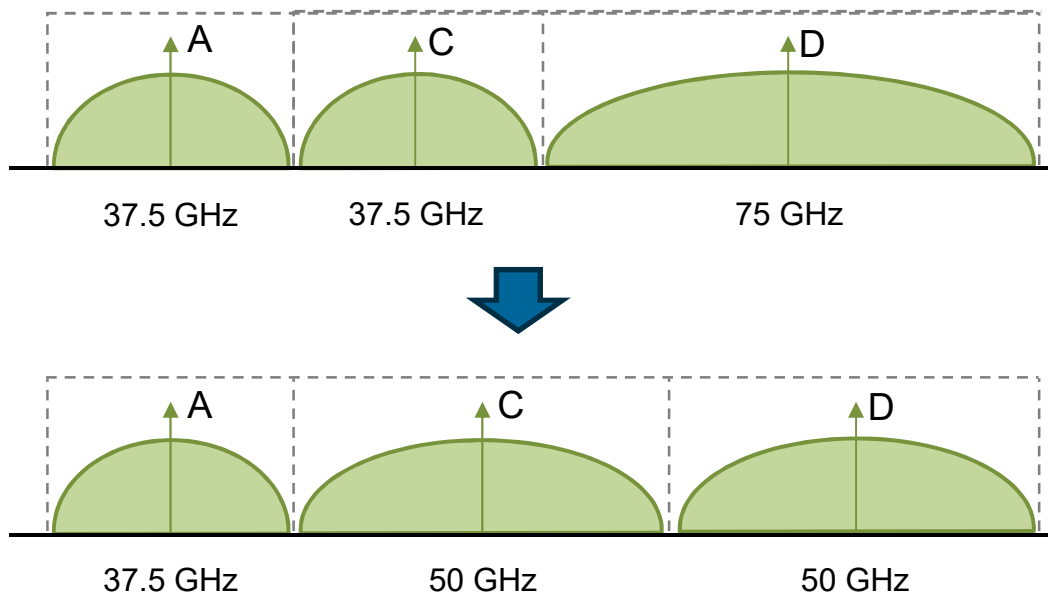
Part I

RSA basics

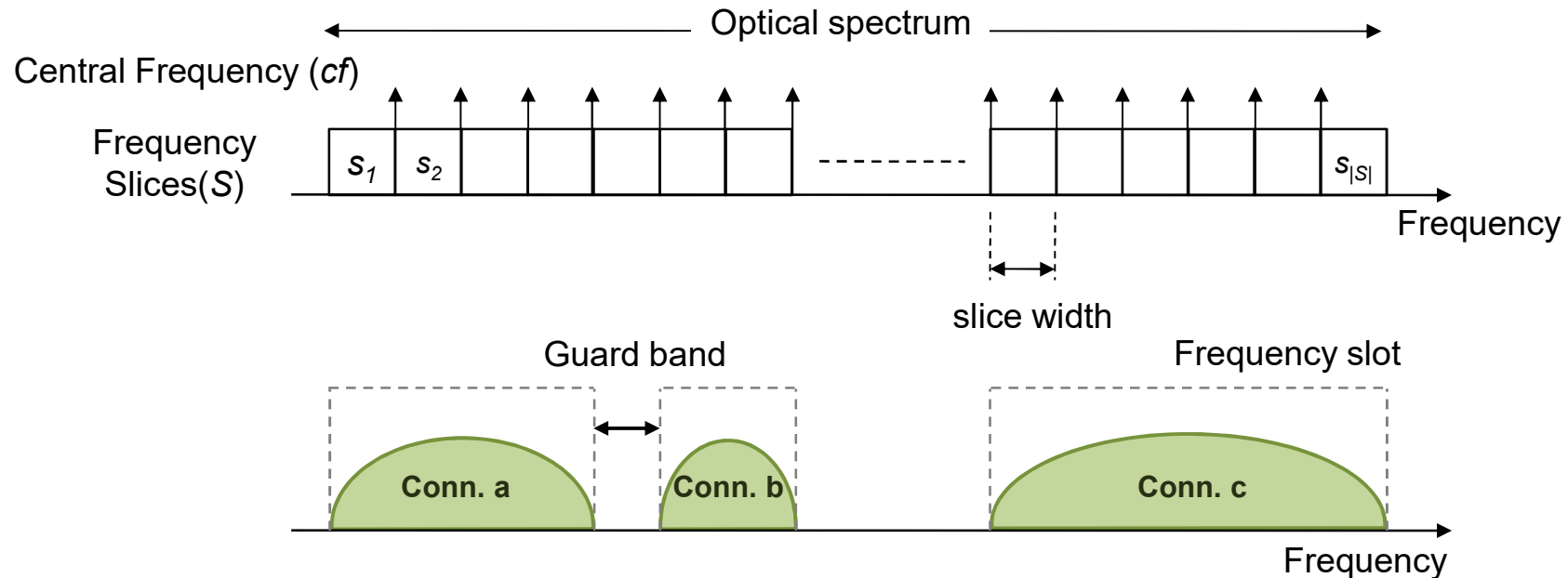
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Elastic Optical Networks

- Flexgrid uses a finer spectrum granularity.
 - The optical spectrum is divided into frequency slices (e.g. 12.5GHz).
- It brings features that are not offered by the fixed grid networks, such as
 - **flexible** bandwidth allocation.
 - transporting optical connections with a capacity **beyond 100Gb/s**
 - **elasticity** against time-varying traffic.



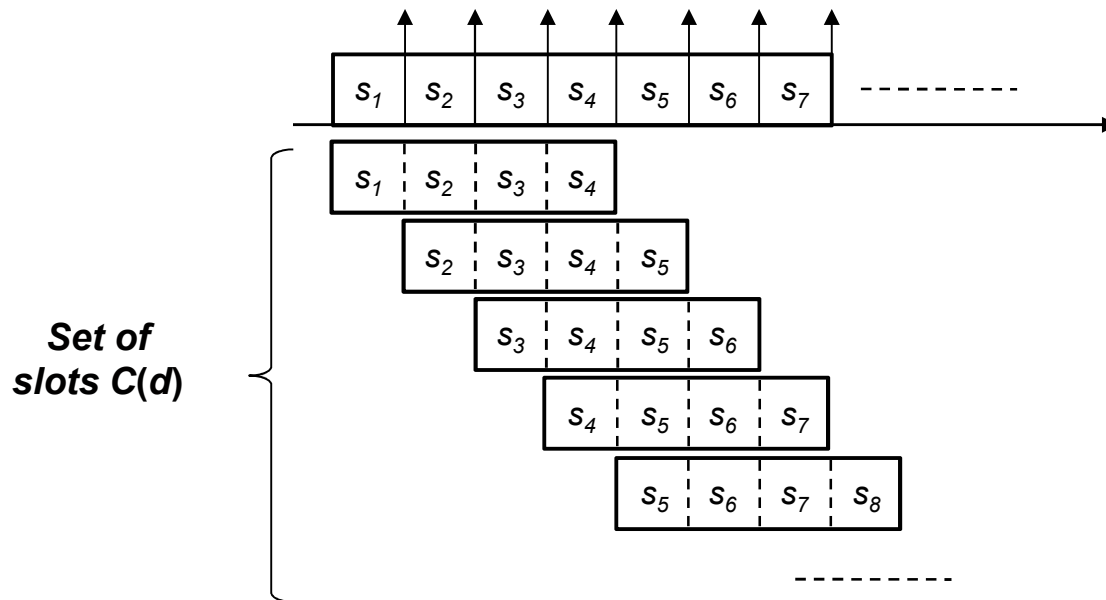
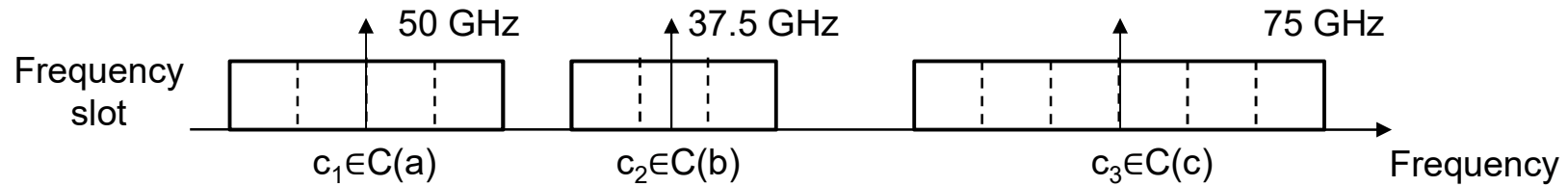
Spectrum allocation



Spectrum allocation entail dealing with two constraints:

- **spectrum continuity** along the links of a given routing path: the same slices must be used in all links of the path,
- **spectrum contiguity**: the allocated slices must be contiguous in the spectrum.

Slices and Slots

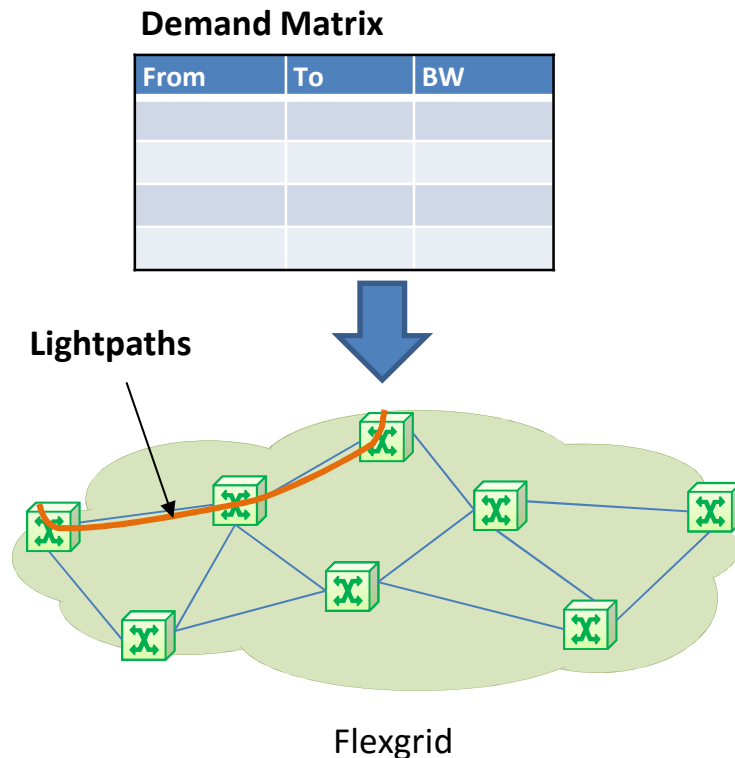


$C(d)$ pre-computation

INPUT S, d	
OUTPUT $C(d)$	
1:	Initialize: $C(d) \leftarrow 0_{[S -n_d+1 \times S]}$
2:	for each i in $[0, S -n_d]$ do
3:	for each s in $[i, i+n_d-1]$ do
4:	$C(d)[s]=1$
5:	return $C(d)$

Basic RSA Problem Statement

- Given:
 1. a graph $G(N,E)$, where N is the of nodes and a set of optical fibers E connecting those nodes;
 2. the characteristics of the optical spectrum (i.e., spectrum width, frequency slice width) and the set of modulation formats;
 3. a traffic matrix D with the amount of bitrate exchanged between each pair of locations in N ;
- Output: the **Route and Spectrum Allocation** for each demand in D .
- Objective: one or more among:
 - Minimize the amount of bitrate blocked,
 - Minimize the total amount of used slices,
 - Minimize the total number of links used,
 - etc.



Link-path Slot Assignment Formulation

Pre-computed Parameters

- $P(d)$ Set of predefined candidate paths for demand d .
- $C(d)$ Set of slots for demand d .
- δ_{pe} Equal to 1 if path p uses link e , 0 otherwise.
- γ_{cs} Equal to 1 if slot c includes slice s , 0 otherwise.

Variables

- x_d Binary. Equal to 1 if demand d is rejected, 0 otherwise.
- y_{pc} Binary. Equal to 1 if slot c is assigned to path p and 0 otherwise

(LP - CA) $\min \sum_{d \in D} x_d \cdot b_d$

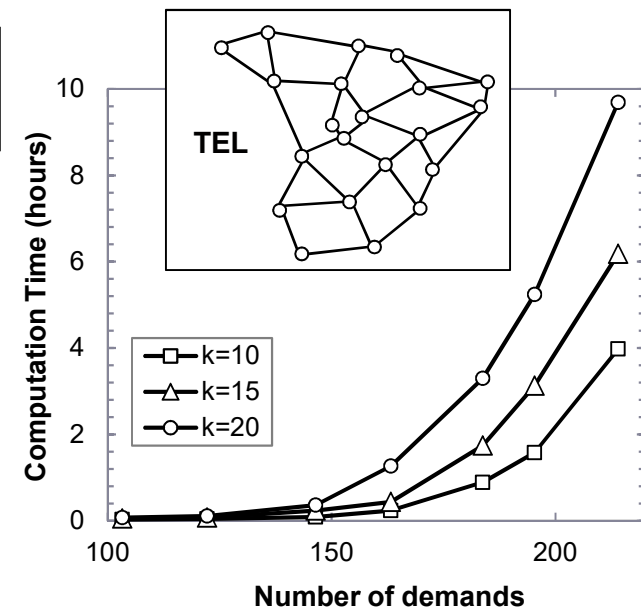
$O(|P(d)| \cdot |D| \cdot |C|)$ variables
 $O(|D| + |E| \cdot |S|)$ constraints

subject to:

$$\sum_{p \in P(d)} \sum_{c \in C(d)} y_{pc} + x_d = 1 \quad \forall d \in D$$

$$\sum_{d \in D} \sum_{p \in P(d)} \sum_{c \in C(d)} \gamma_{cs} \cdot \delta_{pe} \cdot y_{pc} \leq 1 \quad \forall e \in E, s \in S$$

Solved using CPLEX



* L. Velasco et al., "Solving Routing and Spectrum Allocation Related Optimization Problems: from Off-Line to In-Operation Flexgrid Network Planning," (Invited Tutorial) IEEE/OSA Journal of Lightwave Technology (JLT), vol. 32, pp. 2780-2795, 2014.

Topology Design as a RSA Problem

- Given:
 1. a connected graph $G(N,E)$, where N is the set of locations and E the set of optical fibers that can be used;
 2. the characteristics of the optical spectrum and modulation formats;
 3. a traffic matrix D ;
- Output:
 1. The route and spectrum allocation for each demand in D .
 2. **The links that need to be equipped;**
- Objective: **Minimize number of links to be equipped** to transport the given traffic matrix.

Node-link SA Formulation

Variables

- w_{dec} Binary. Equal to 1 if demand d uses slot c in link e , 0 otherwise
 z_e Binary. Equal to 1 if link e is opened, 0 otherwise

$$(NL - CA) \quad \min \quad \sum_{e \in E} z_e$$

subject to:

$$\sum_{e \in E(v)} \sum_{c \in C(d)} w_{dec} = 1 \quad \forall d \in D, v \in \{s_d, t_d\}$$

$$\sum_{e \in E(v)} \sum_{c \in C(d)} w_{dec} \leq 2 \quad \forall d \in D, v \notin \{s_d, t_d\}$$

$$\sum_{\substack{e' \in E(v) \\ e' \neq e}} w_{de'c} \geq w_{dec} \quad \forall d \in D, c \in C(d), v \notin \{s_d, t_d\}, e \in E(v)$$

$$\sum_{d \in D} \sum_{c \in C(d)} \gamma_{cs} \cdot w_{dec} \leq 1 \quad \forall e \in E, s \in S$$

$$\sum_{d \in D} \sum_{c \in C(d)} w_{dec} \leq |S| \cdot z_e \quad \forall e \in E$$

$O(|D| \cdot |E| \cdot |C|)$ variables

$O(|D| \cdot |C| \cdot |N| \cdot |E|)$ constraints

* L. Velasco et al., "Solving Routing and Spectrum Allocation Related Optimization Problems: from Off-Line to In-Operation Flexgrid Network Planning," (Invited Tutorial) IEEE/OSA Journal of Lightwave Technology (JLT), vol. 32, pp. 2780-2795, 2014.

Network Dimensioning as a RSA Problem

- Given:
 1. a connected graph $G(N,E)$, where N is the set of locations and E the set of optical fibers;
 2. the characteristics of the optical spectrum and modulation formats;
 3. a traffic matrix D ;
 4. **the cost of every component, such as optical cross-connects (OXC) and transponder (TP) types specifying its capacity and reach.**
- Output:
 1. The route and spectrum allocation for each demand in D .
 2. **Network dimensioning including the type of OXC and TPs in each location;**
- Objective: **Minimize the total cost** to transport the given traffic matrix.



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Part II

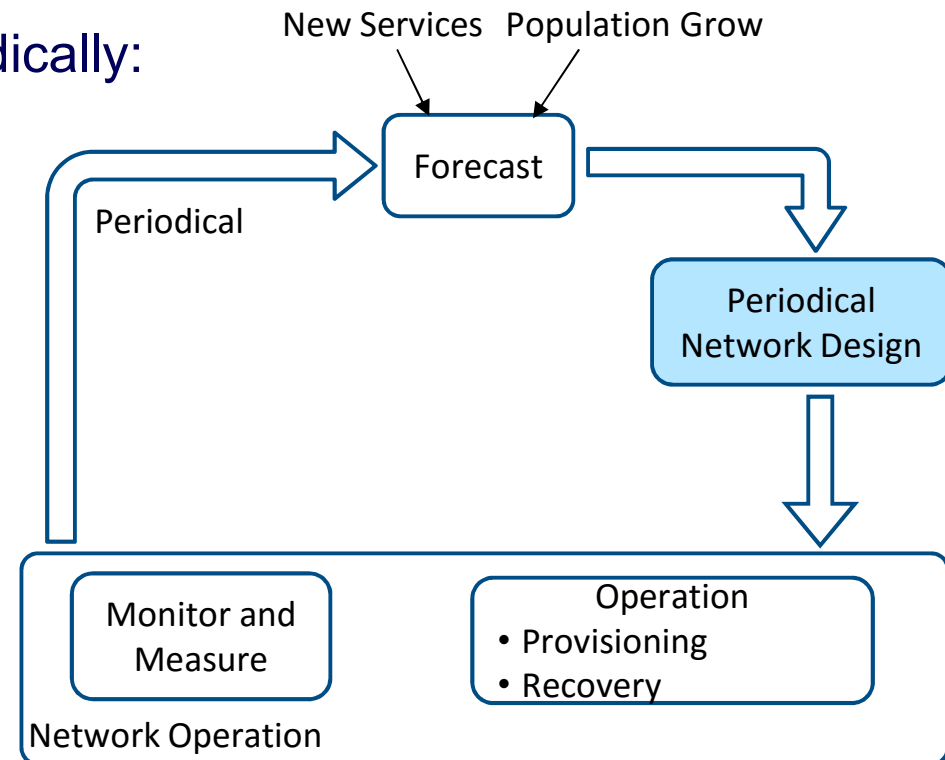
Network Design

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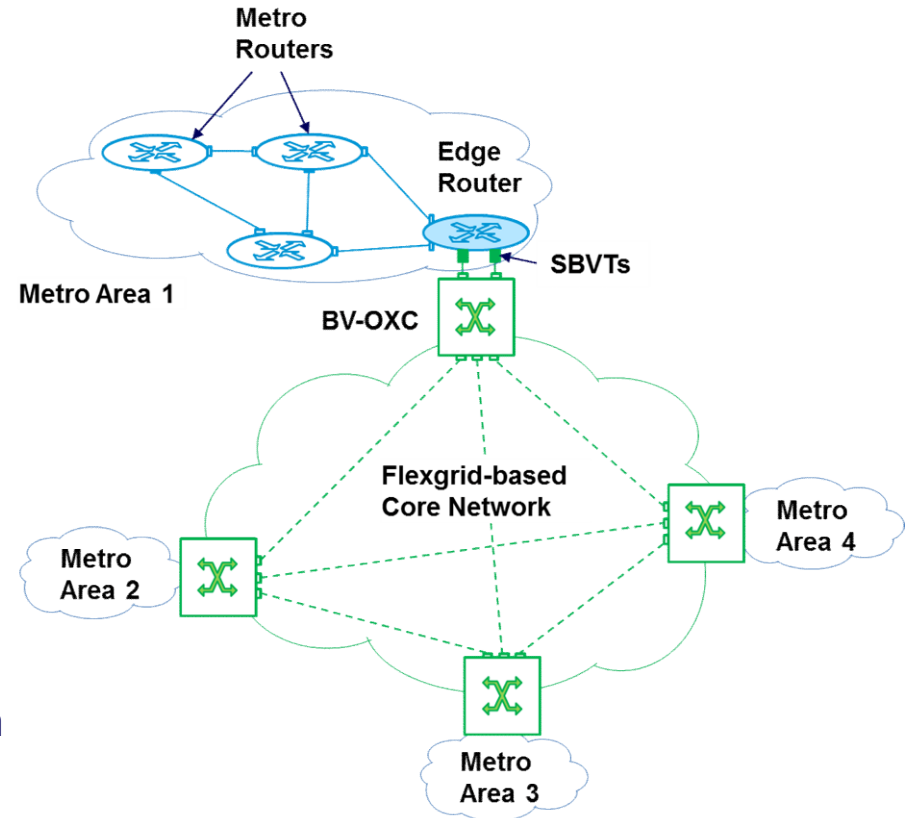
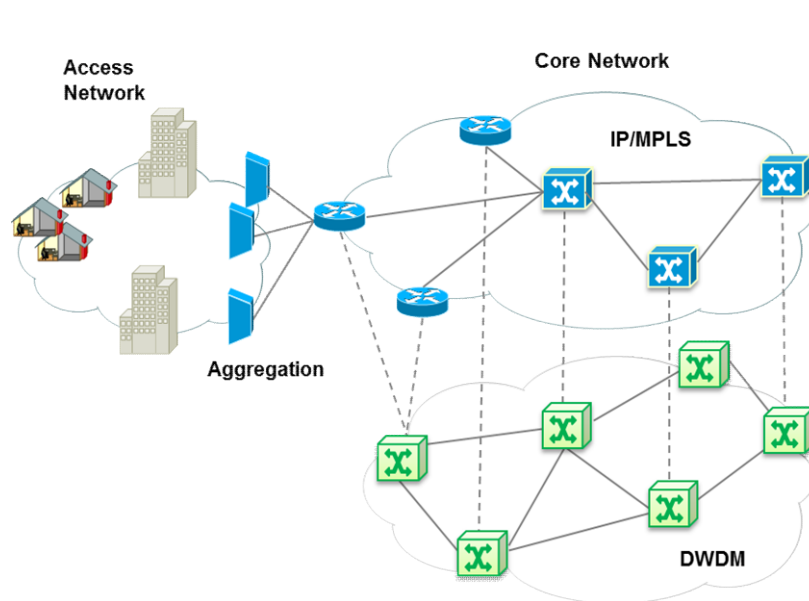
Classical Network life-cycle

- Network planning is performed periodically:

- **Capacity** is installed to guarantee that the network can support the forecast traffic.
- **Long planning cycles** are used to upgrade the network and prepare it for the next planning period.
- Results from network capacity planning are **manually deployed** in the network.



Designing National IP/MPLS Networks with Flexgrid Optical Technology



National IP/MPLS networks have been built on the top of optical networks, and thus the design problem has been typically addressed through a **multilayer IP/MPLS-over-optical** approach.

The multilayer approach is transformed into a single-layer approach where a number of **IP/MPLS metro area networks** performing aggregation are connected through a **flexgrid-based core network**.

* L. Velasco et al., "Saving CAPEX by Extending Flexgrid-based Core Optical Networks towards the Edges," IEEE/OSA Journal of Optical Communications and Networking (JOCN), vol. 5, pp. A171-A183, 2013.

Flexgrid-based Network Design

- The flexgrid-based network design consists in designing a complete network including metro and core networks so as to deploy spectrum-efficient core network.

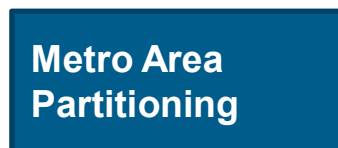
- We define network spectrum efficiency as:
$$\sum_{a \in A} \sum_{\substack{a' \in A \\ a' \neq a}} \frac{b_{aa'}}{\Delta f \cdot B_{\text{mod}}} \bigg/ \sum_{a \in A} \sum_{\substack{a' \in A \\ a' \neq a}} \left[\frac{b_{aa'}}{\Delta f \cdot B_{\text{mod}}} \right]$$

- Two phases are considered:

1. Partitioning the Network in Metro Areas: The complete set of locations is grouped into a number of metro areas. The core network convey aggregated flows between metro areas. The slot width used in the flexgrid-based core network is taken into account to guarantee enough spectral efficiency.

2. Metro and Core networks design.

- Set of locations
- Potential metros
- Traffic matrix
- Slice width



- Traffic Matrices
- Metro Areas

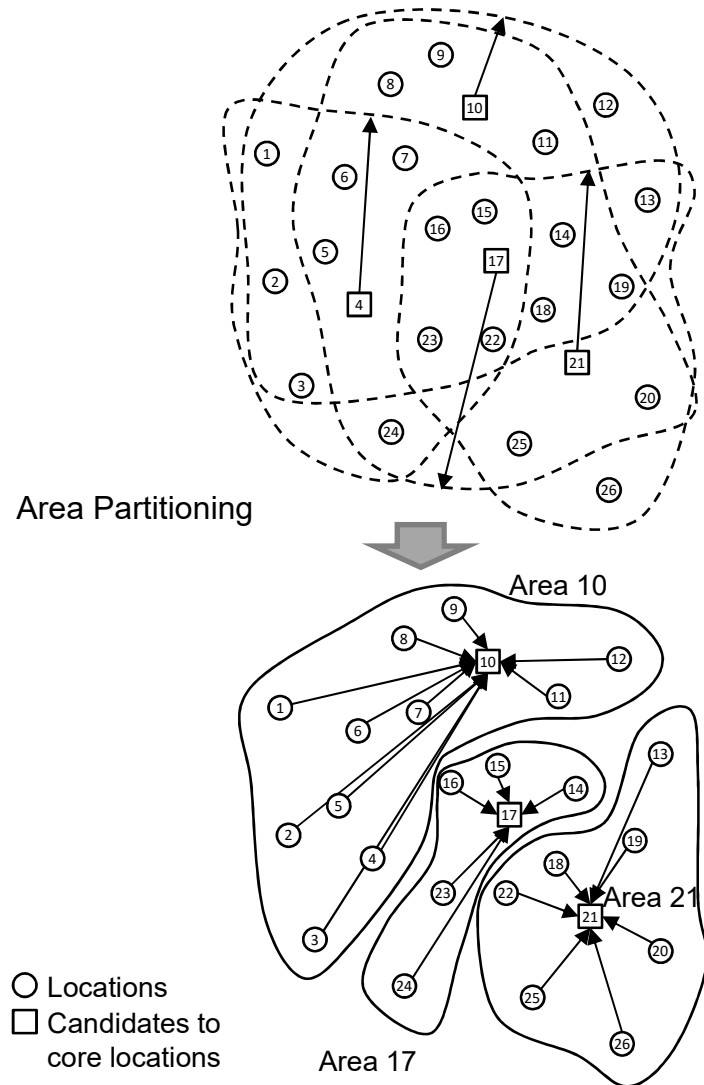


Design for each network



Network Graphs,
Equipments and costs

Area Partitioning Problem



Given:

- a set L of Locations,
- a subset $A \subseteq L$ of locations that can be selected as core locations. Since each core location $a \in A$ could entail an area to be created, the set A also represents the set of areas,
- the subset $A(l) \subseteq A$ of core locations where each location l can belong to,
- the location-to-location traffic matrix,
- the considered slice width (Δf) for the flexgrid network.

Output: The set of areas. For each area a , the locations belonging to that area and its internal traffic. The set of aggregated traffic between areas ($b_{aa'}$).

Objective: Maximize the aggregated traffic exchanged between areas ($\sum_{a \in A} \sum_{a' \in A} b_{aa'}$) subject to ensuring a minimum spectral efficiency for the core network.

* L. Velasco et al. "Saving CAPEX by Extending Flexgrid-based Core Optical Networks towards the Edges," IEEE/OSA JOCN, vol. 5, pp. A171-A183, 2013.

Network Design Problem

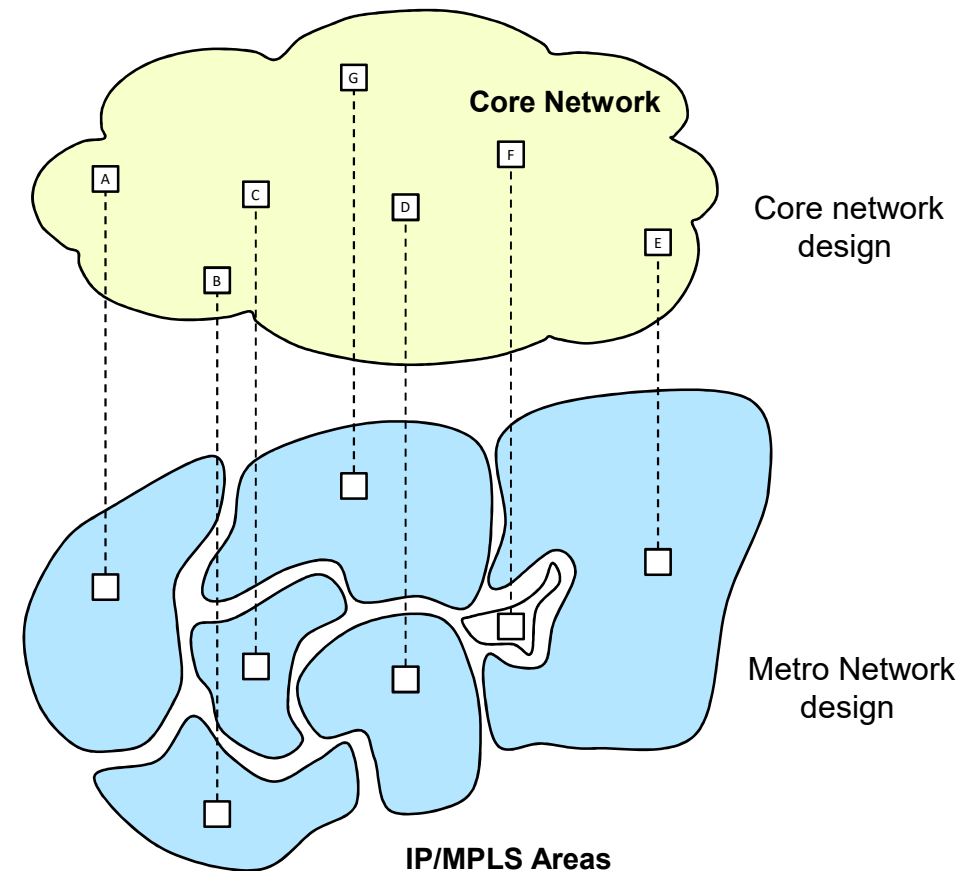
Given:

- a network topology represented by a graph $G_C(N_C, L)$, being N_C the set of core locations and L the set of fibre links connecting two locations,
- a set S of available slices of a given spectral width for each link in L ,
- a set D_C of IP/MPLS demands to be transported,
- BV-OXC cost, which include a fixed cost for common hardware and a variable cost that depends on the nodal degree and the number of local ports (patch panels can be used to connect optical fibres provided that no local signals are dropped); a cost for every optical amplifier (OA) to be equipped in the used fibre links; a cost of every 3R needed to electronically regenerate optical signals at intermediate nodes. Different types of 3Rs may exist as a function of their capacity and reach.

Output:

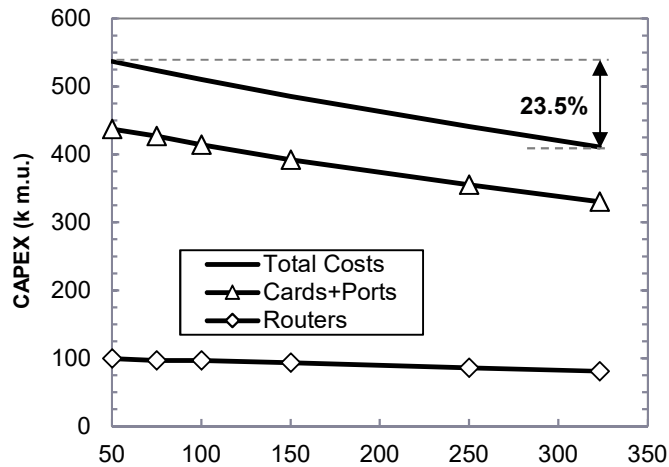
- the optical network, including patch panels, BV-OXCs and its configuration, OA and fibres,
- the location and capacity of each of the 3Rs needed.

Objective: Minimize the expected CAPEX for the core network designed for the given set of demands.

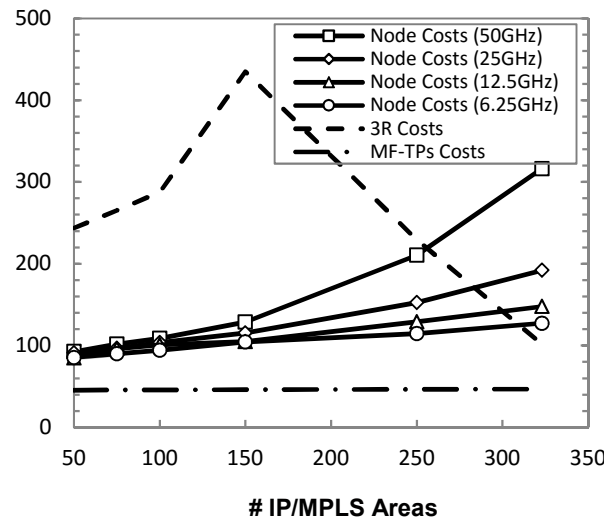


Design results

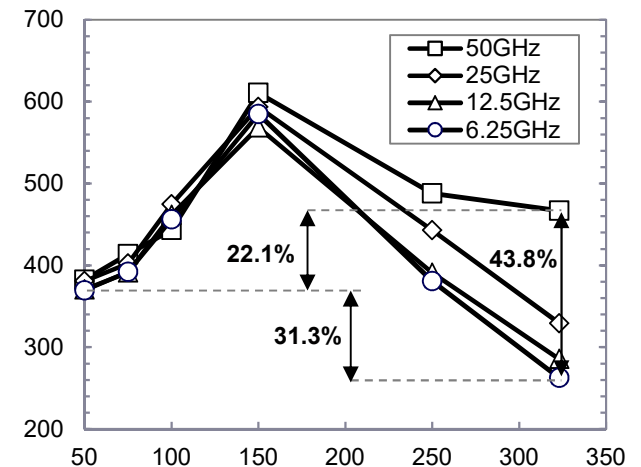
Aggregated and breakdown IP/MPLS CAPEX.



Flexgrid core network CAPEX for each considered slot width.

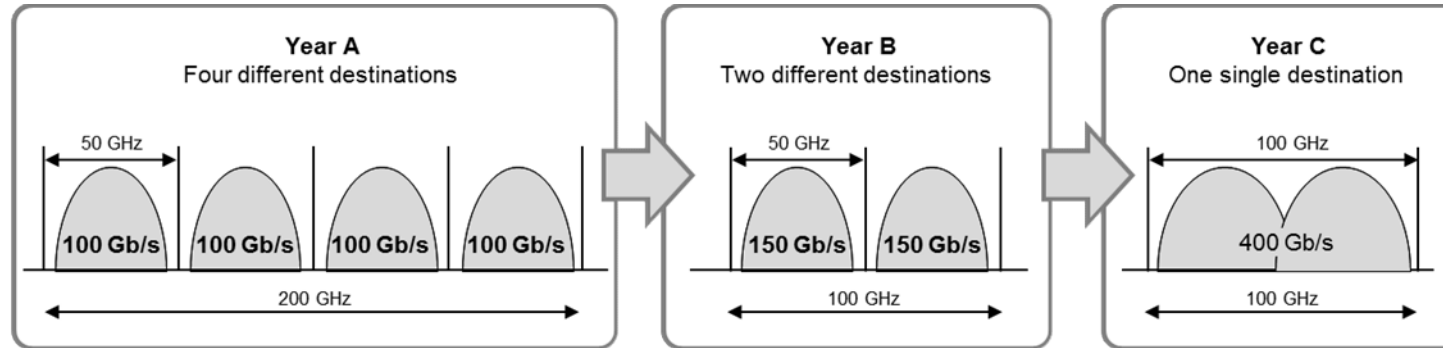


Core network costs breakdown

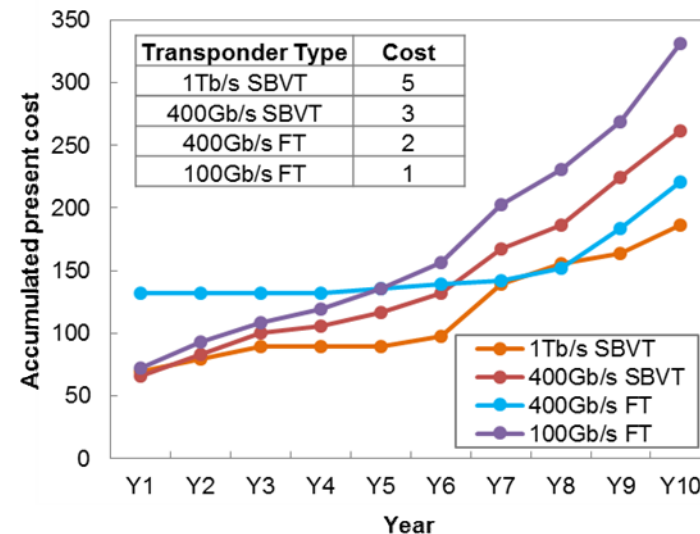
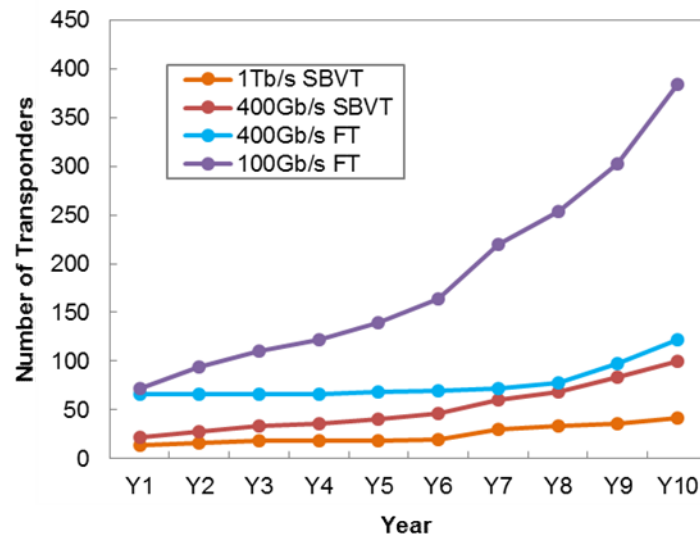


- Significant savings can be obtained when the core network extends towards the edges increasing the number of areas that are connected.
 - 31% at the flexgrid core network
 - 23% at the IP/MPLS networks
- The flexgrid core network need to use finer slices (12.5 or even 6.25 GHz)
 - grooming is done, in part, at the optical layer considerably reducing that done at the IP/MPLS one.
 - The capacity and the number of IP/MPLS routers and ports can be reduced.
- 3R regeneration is needed as a result of super-channels, e.g. 400Gb/s
 - it might be mitigated by using e.g. 4x100Gb/s, increasing thus the reach of the optical signals.

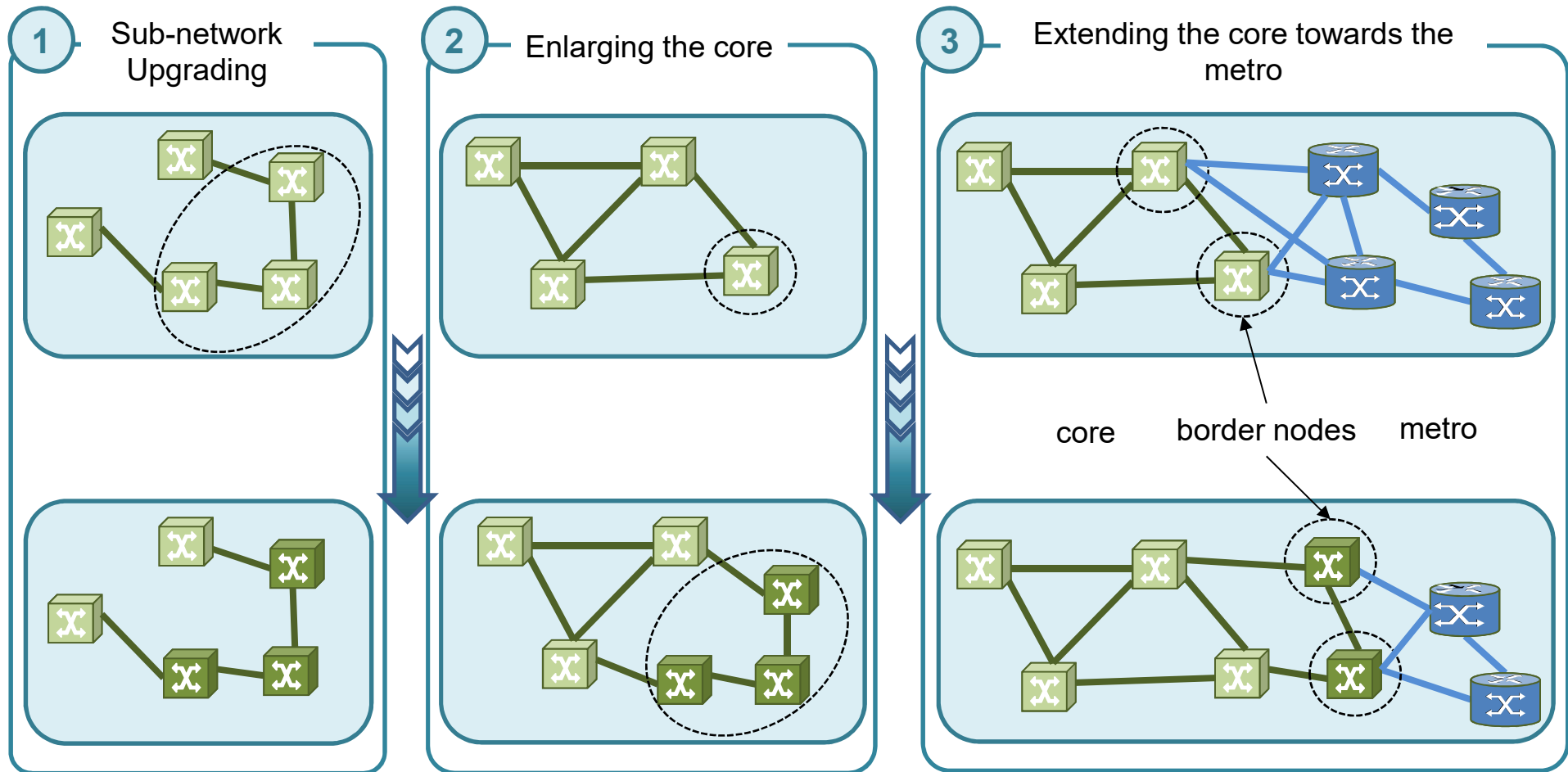
SBVTs under Static traffic



Gb/s	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
<=100	85.7%	61.9%	47.6%	33.3%	19.0%	19.0%	4.8%	4.8%	4.8%	4.8%
(100-200]	14.3%	33.3%	42.9%	52.4%	61.9%	42.9%	28.6%	14.3%	14.3%	0.0%
(200-300]	0.0%	4.8%	9.5%	9.5%	9.5%	23.8%	28.6%	28.6%	9.5%	14.3%
(300-400]	0.0%	0.0%	0.0%	4.8%	4.8%	4.8%	23.8%	33.3%	33.3%	14.3%
>400	0.0%	0.0%	0.0%	0.0%	4.8%	9.5%	14.3%	19.0%	38.1%	66.7%



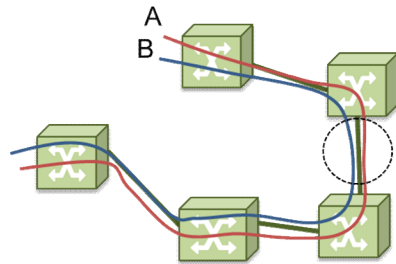
Migrating Towards Flexgrid Technology



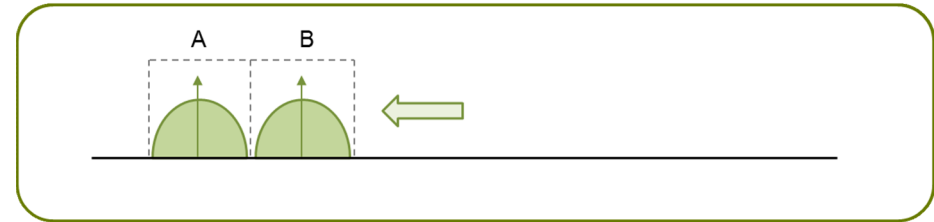
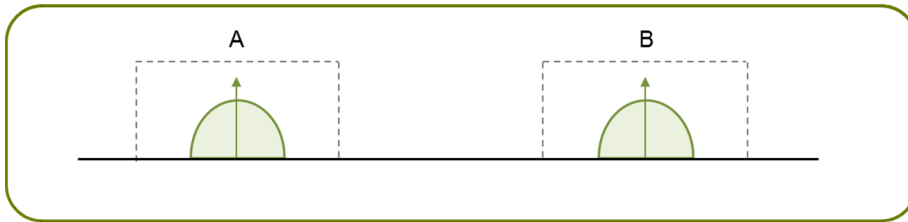
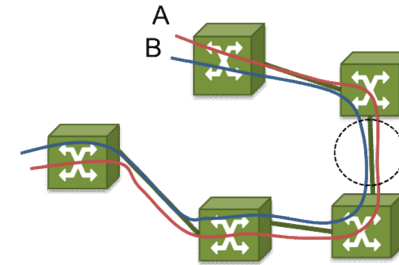
* M. Ruiz et al, "Planning Fixed to Flexgrid Gradual Migration: Drivers and Open Issues," IEEE Communications Magazine, vol. 52, pp. 70-76, 2014.

Migrating connections

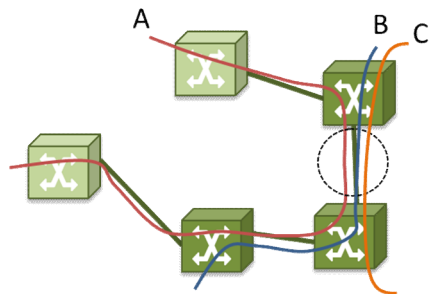
Fixed grid



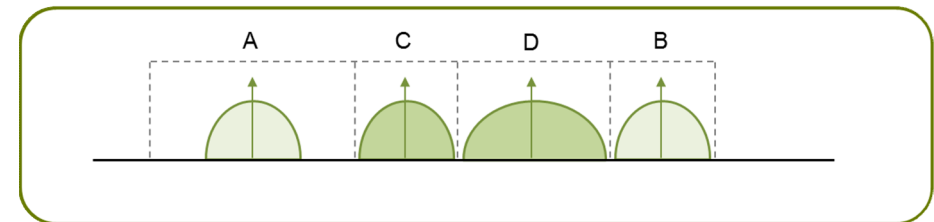
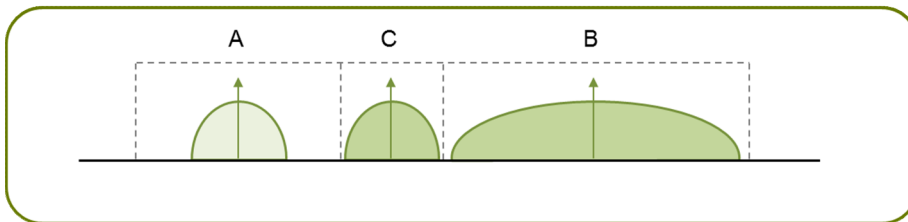
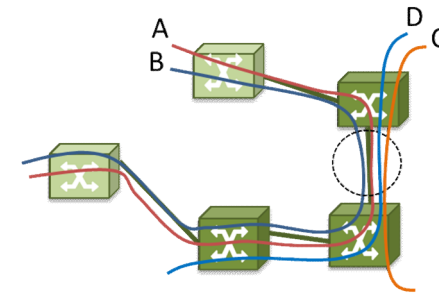
Flexgrid



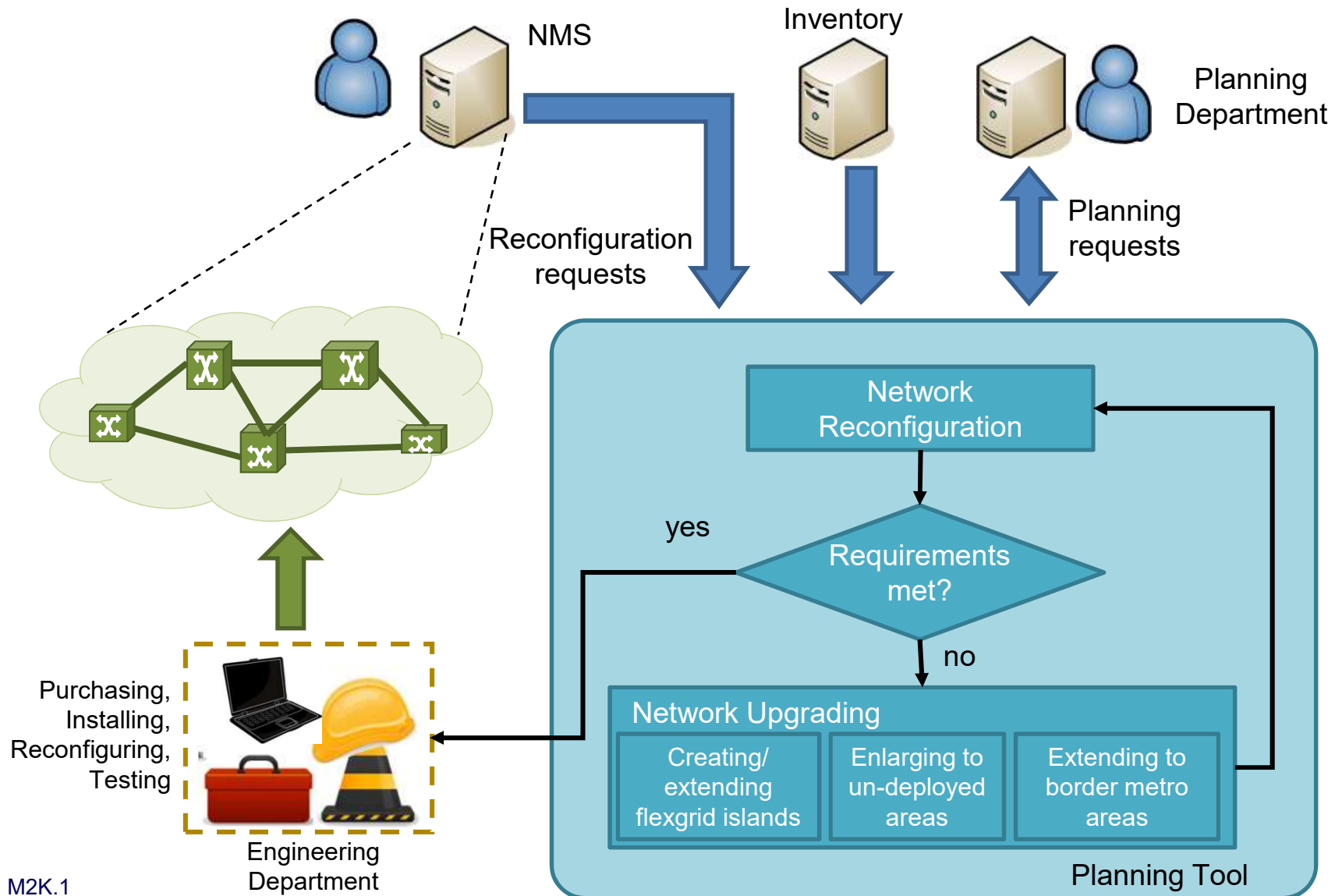
Mixed grid



Mixed grid



Migration flow chart





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Part III

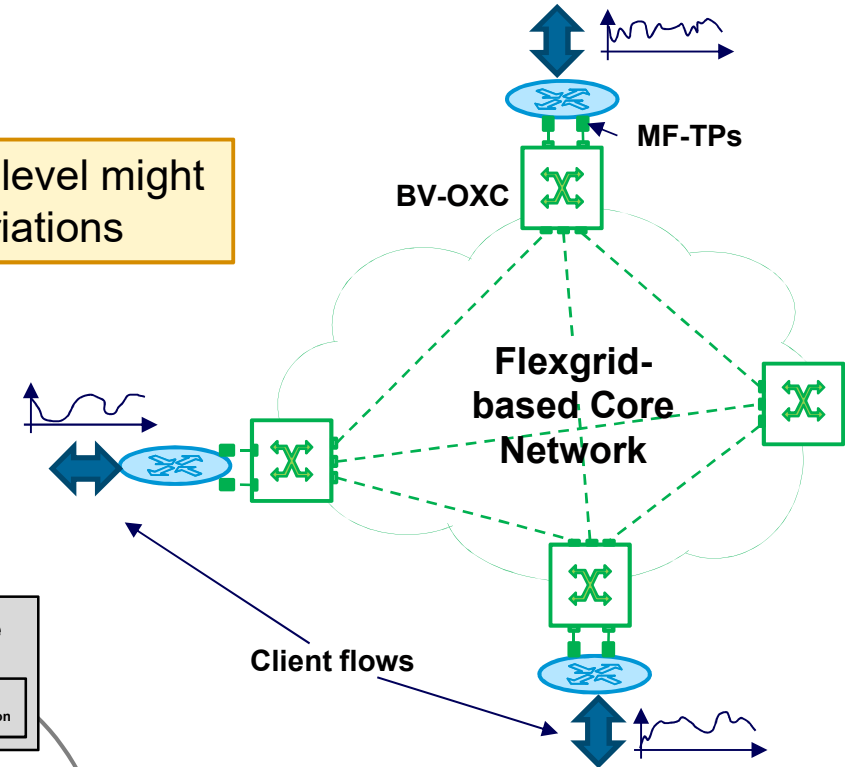
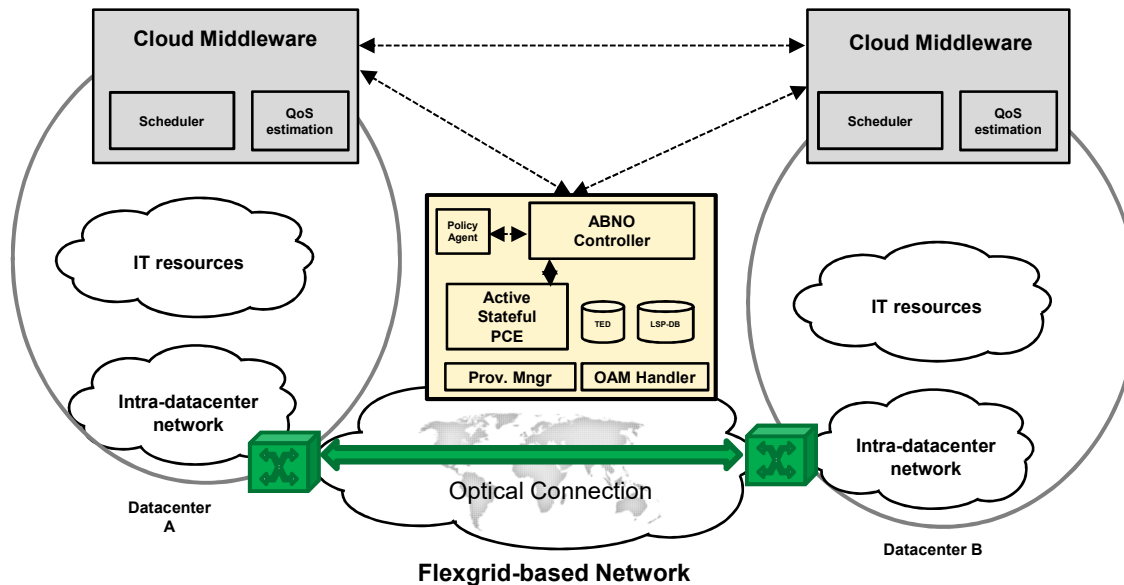
RSA under Dynamic Traffic

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Source of traffic variations

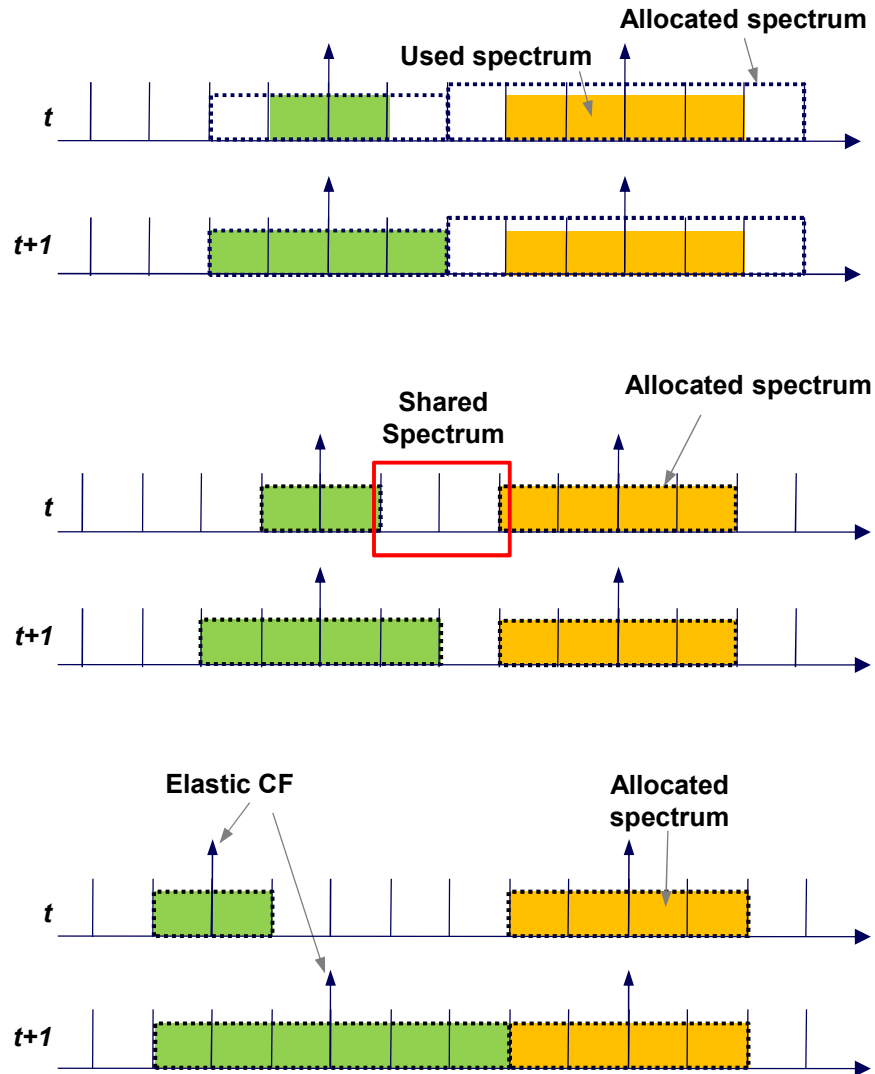
Reducing aggregation level might increase traffic variations

Datacenter interconnection to transfer bulk data



* L. Velasco, et al., "Cross-Stratum Orchestration and Flexgrid Optical Networks for Datacenter Federations," IEEE Network Magazine, vol. 27, pp. 23-30, 2013.

Elastic Spectrum Allocation Policies



Fixed: both the assigned CF and spectrum width do not change in time.

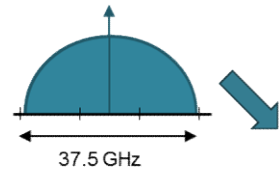
Semi-Elastic: the assigned CF is fixed but the allocated spectrum may vary.

- At each time interval, the allocated spectrum corresponds to the utilized spectrum.
- Spectrum increments/decrements are achieved by allocating/releasing frequency slices.
- The frequency slices can be shared between neighboring demands, but used by, at most, one demand in a time interval.

Elastic: both the assigned CF and the spectrum width can be subject to change in each time interval.

* M. Klinkowski et al., "Elastic Spectrum Allocation for Time-Varying Traffic in Flexgrid Optical Networks," IEEE Journal on Selected Areas in Communications (JSAC), vol. 31, pp. 26-38, 2013

Example of Re-optimisation (Defragmentation)



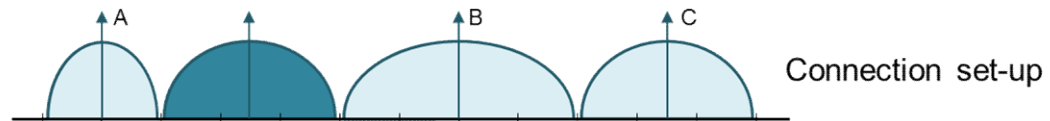
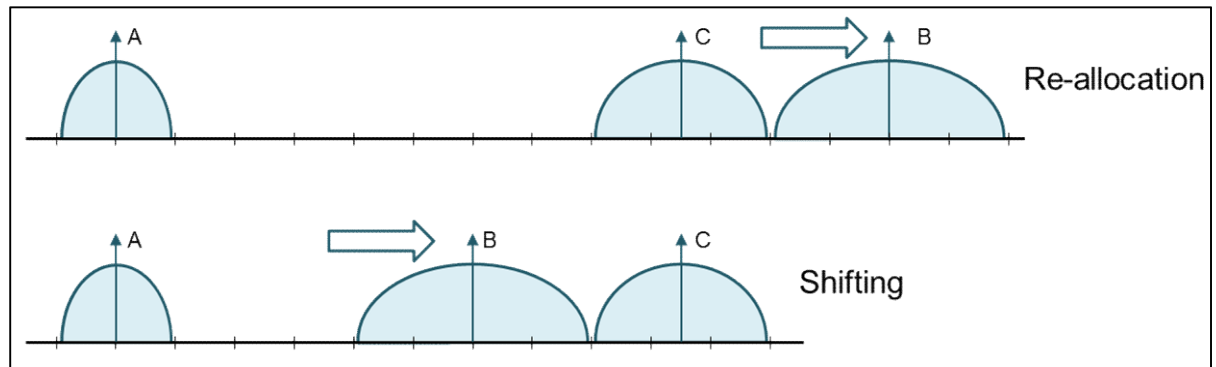
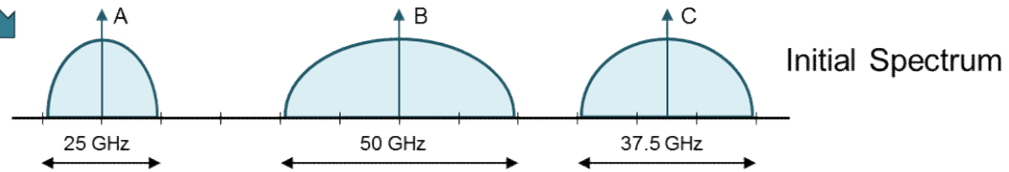
Given:

- an optical network, represented by a graph $G(N, E)$,
- a set S of frequency slots available in each link $e \in E$,
- a set P of already established paths,
- a new path ($newP$) to be established in the network. A route for the path has been already selected but there is no feasible spectrum allocation,
- the threshold num of paths to be reallocated.

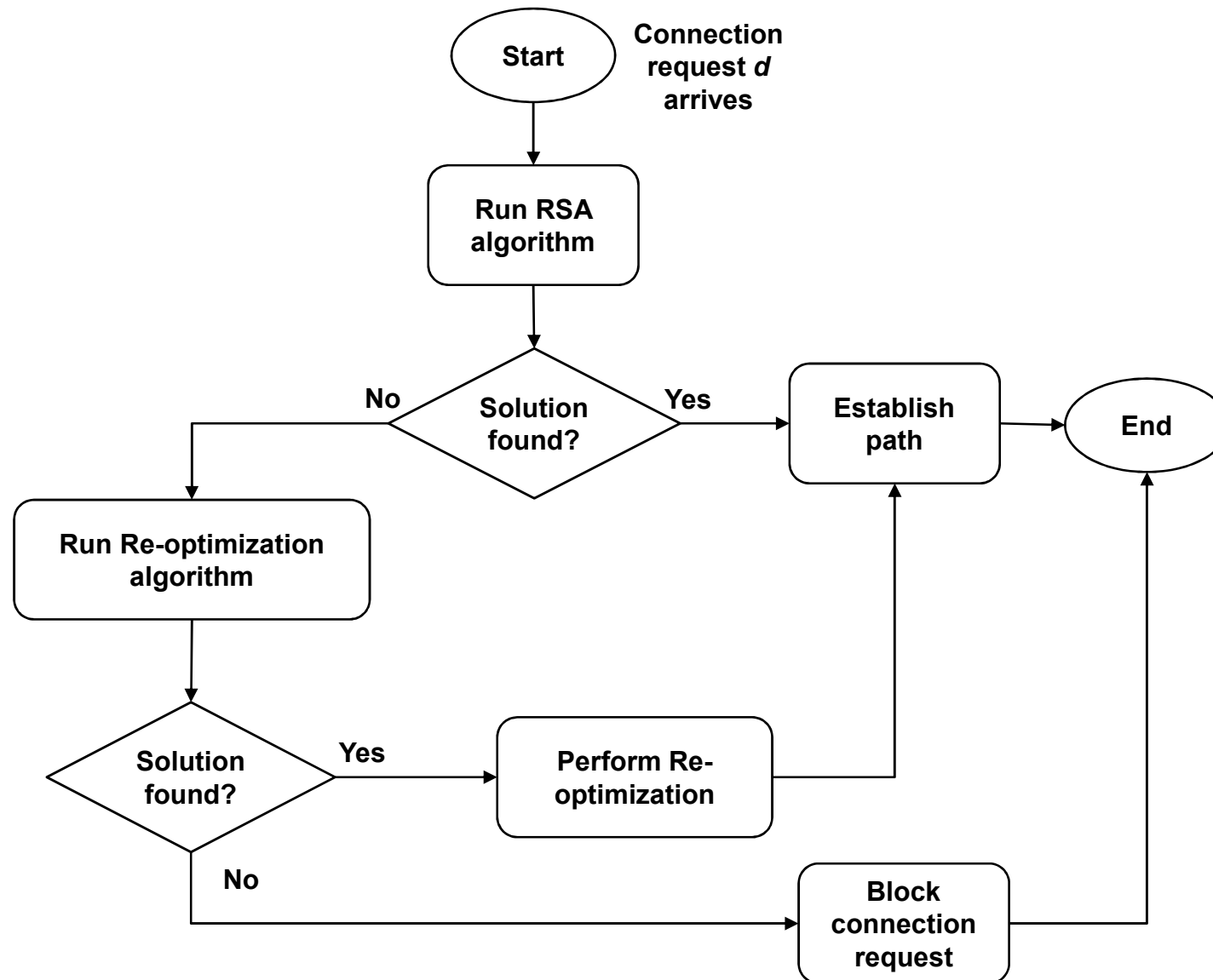
Output:

- for each path to be reallocated, its new spectrum allocation,
- the spectrum allocation for $newP$.

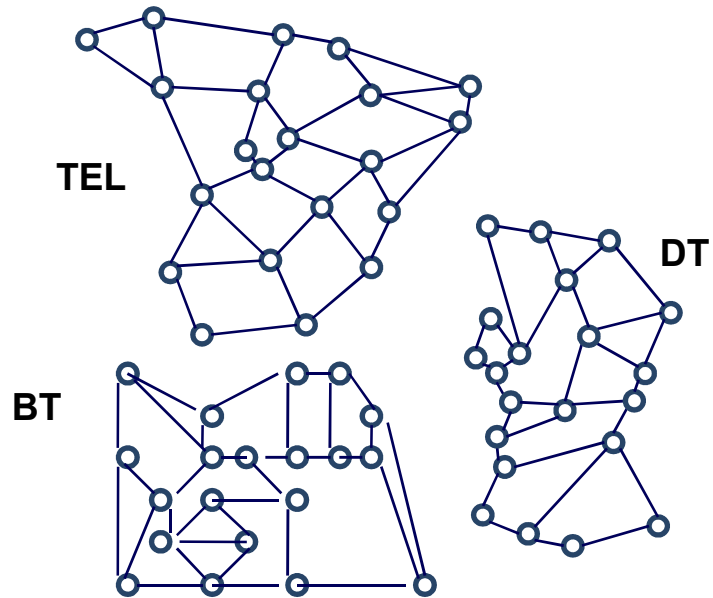
Objective: Minimize the amount of paths to be reallocated so to fit $newP$ in.



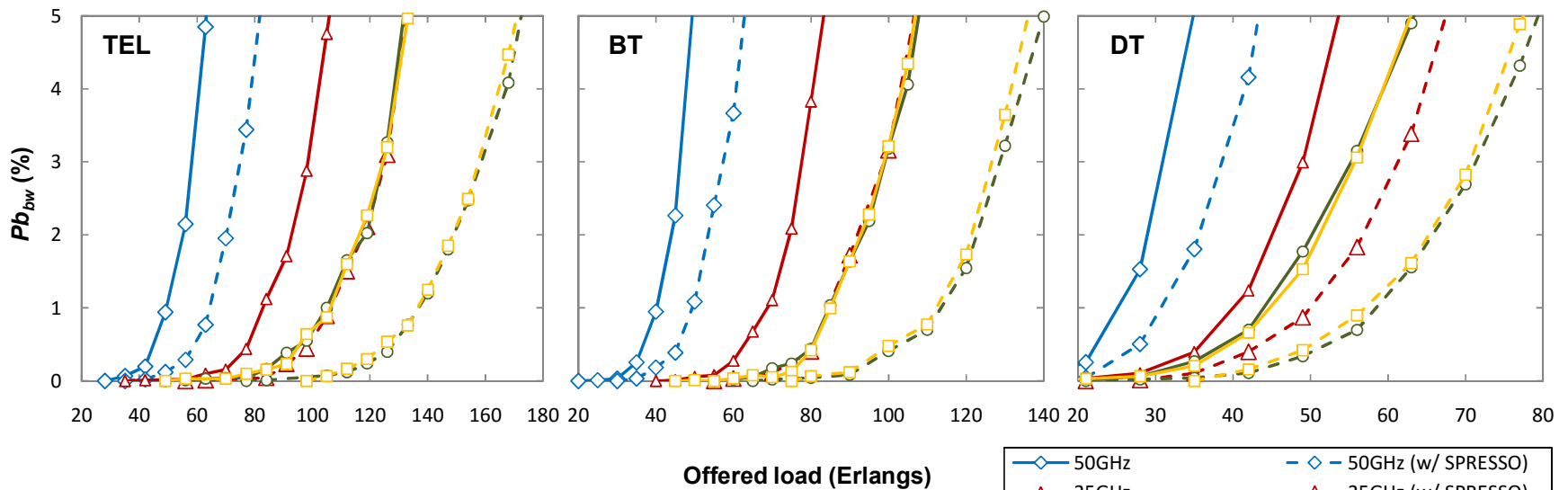
Provisioning-triggered re-optimization



Gains of Defragmentation

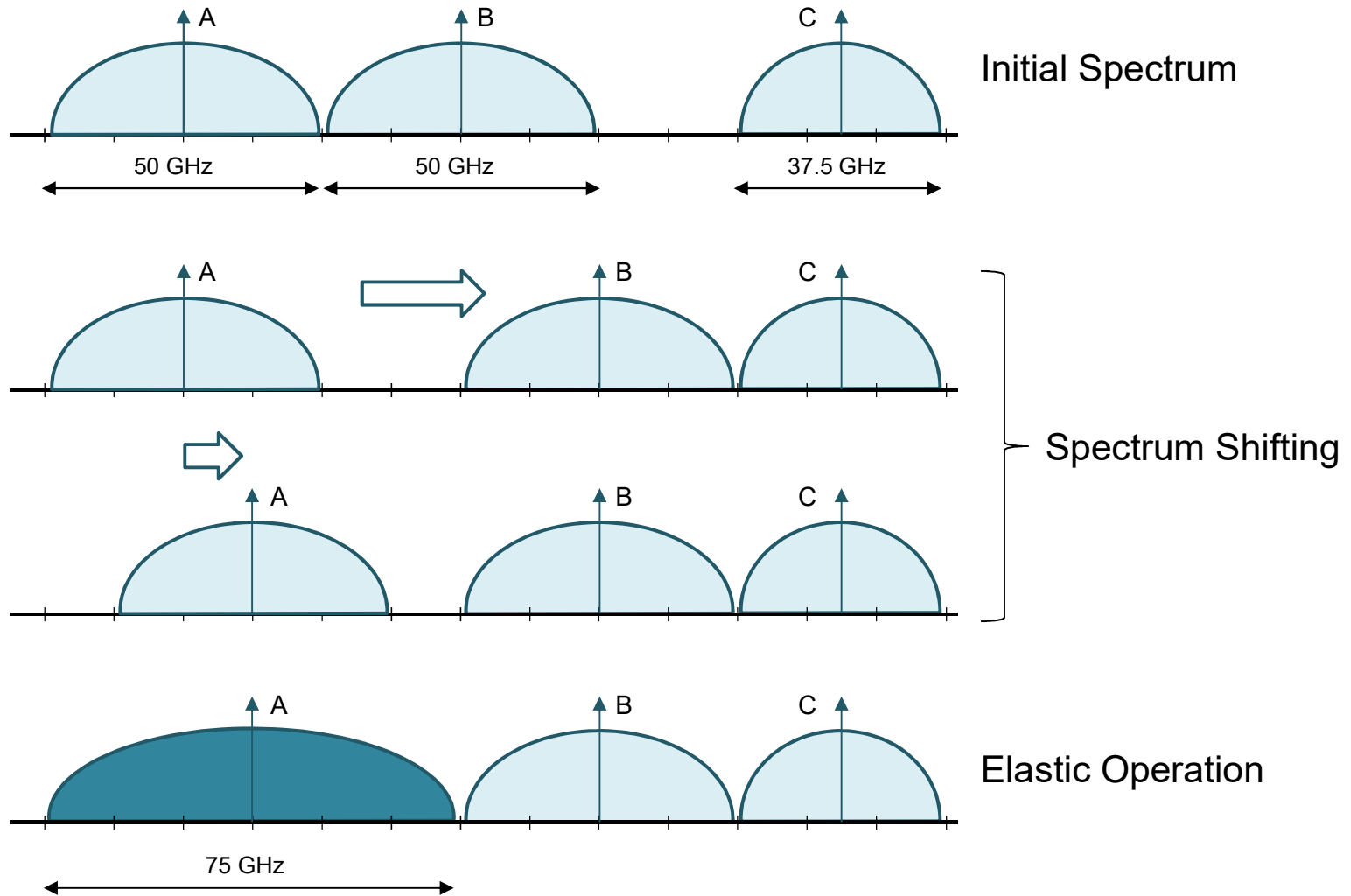


Network	25 GHz	12.5 GHz	6.25 GHz
TEL	30,4%	28,4%	30,3%
BT	22,9%	23,0%	34,1%
DT	22,2%	24,8%	33,0%



* A. Castro, et al., "Dynamic Routing and Spectrum (Re)Allocation in Future Flexgrid Optical Networks," Elsevier Computers Networks, vol. 56, pp. 2869-2883, 2012.

Example of Re-optimisation (Elasticity)



Elastic Operations and Hitless Defragmentation

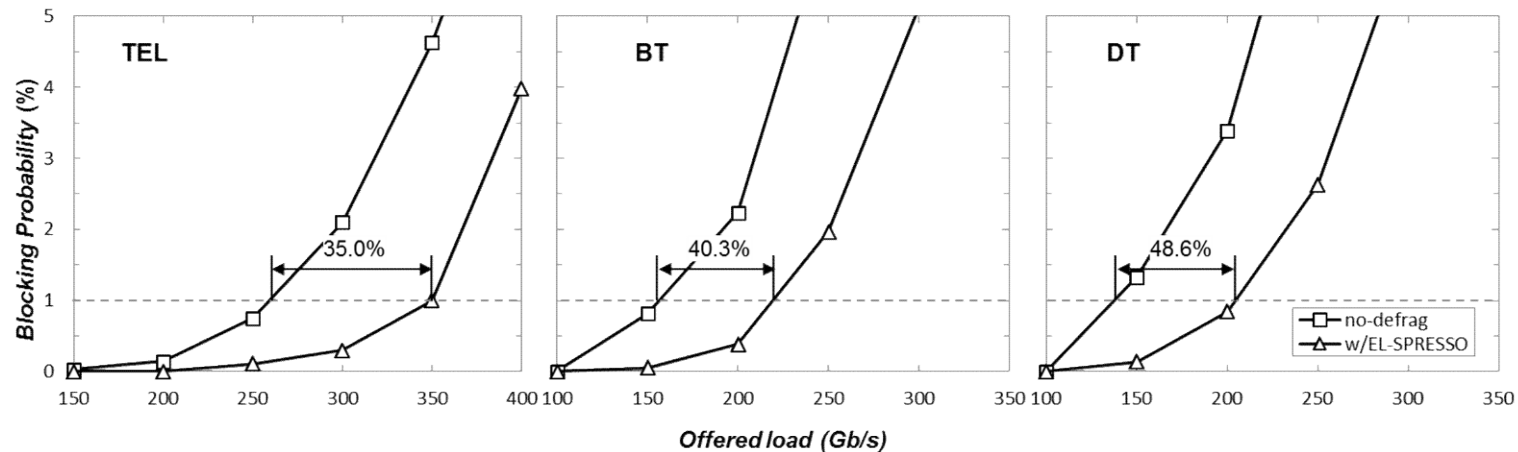
The EL-SPRESSO problem can be formally stated as:

Given:

- a core network topology represented by a graph $G(N, E)$;
- a set S of available slots of a given spectral width for every link in E ;
- a set L of LSPs already established on the network; each LSP l is defined by the tuple $\{R_l, fc_l, m_l\}$, where the ordered set $R_l \subseteq E$ represents its physical route, fc_l its central frequency and m_l the amount of frequency slots.
- a LSP $p \in L$ for which a request has arrived to increase the SA to number of frequency slots, m_p .

Output: the list of LSPs to be reallocated and the new values for the SA for the given LSP p : $\{R_p, fc_p, m_p\}$.

Objective: minimize the number of reallocations to be performed.



* F. Paolucci et al. "Active PCE Demonstration performing Elastic Operations and Hitless Defragmentation in Flexible Grid Optical Networks," Springer Photonic Network Communications, vol. 29, pp. 57-66, 2015.

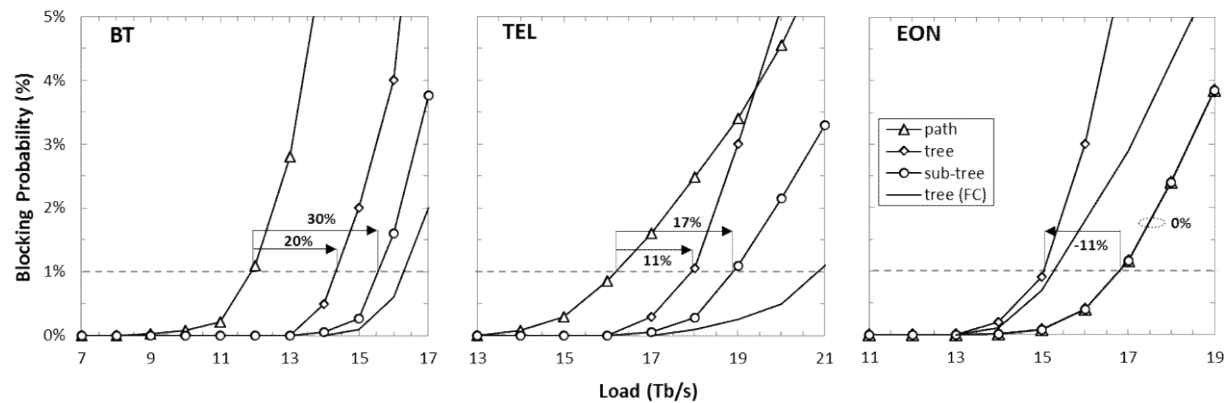
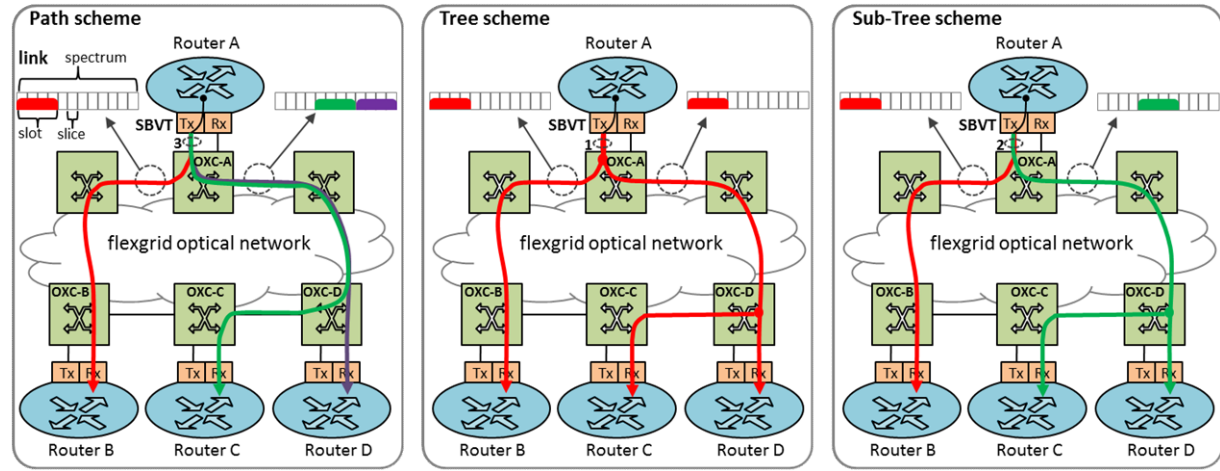
LightTrees

Given:

- A network topology represented by a graph $G(V,E)$;
- a set S of available frequency slices of a given spectral width in each link;
- a set of SBVTs installed in every router;
- a set of multicast demands to be served identified by the tuple $\langle s_d, T(d), b_d \rangle$;
- a selected routing scheme (path, tree, or sub-tree).

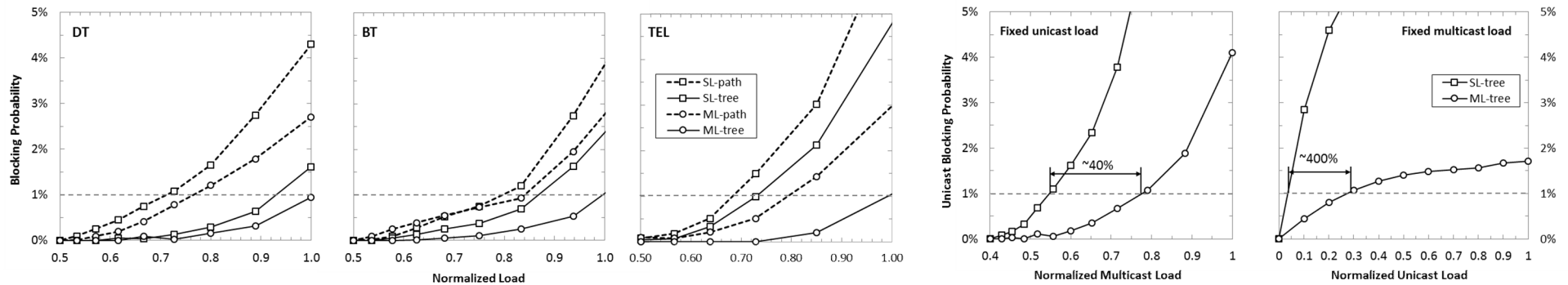
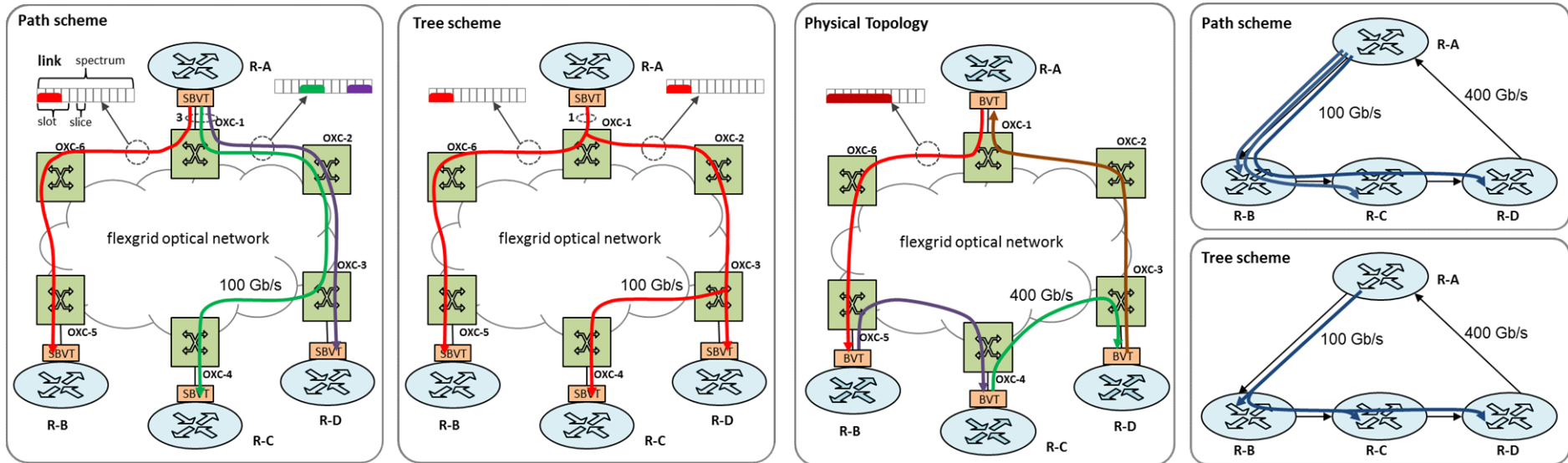
Output: the RSA for each connection.

Objective: minimize the amount of rejected (blocked) multicast demands (main objective) and the number of used Tx SBVT modules (secondary objective).



* M. Ruiz and L. Velasco, "Performance Evaluation of Light-tree Schemes in Flexgrid Optical Networks," in IEEE Communications Letters, vol. 18, pp. 1731-1734, 2014.

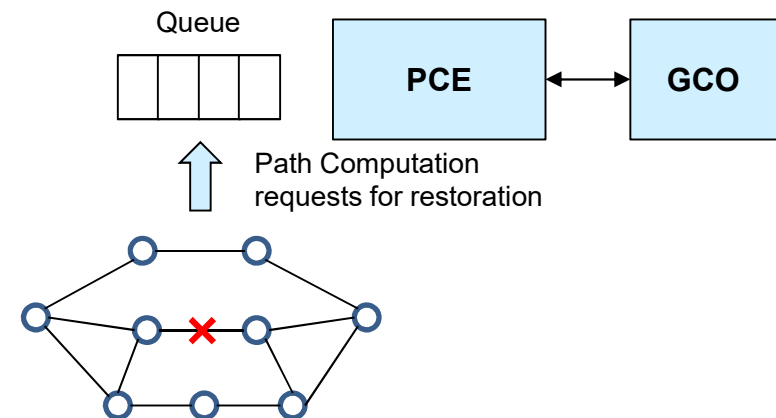
Multicast connections: Optical vs Multilayer



* M. Ruiz and L. Velasco, "Serving Multicast Requests on Single Layer and Multilayer Flexgrid Networks," IEEE/OSA Journal of Optical Communications and Networking (JOCN), vol. 7, pp. 146-155, 2015.

Bulk path computation

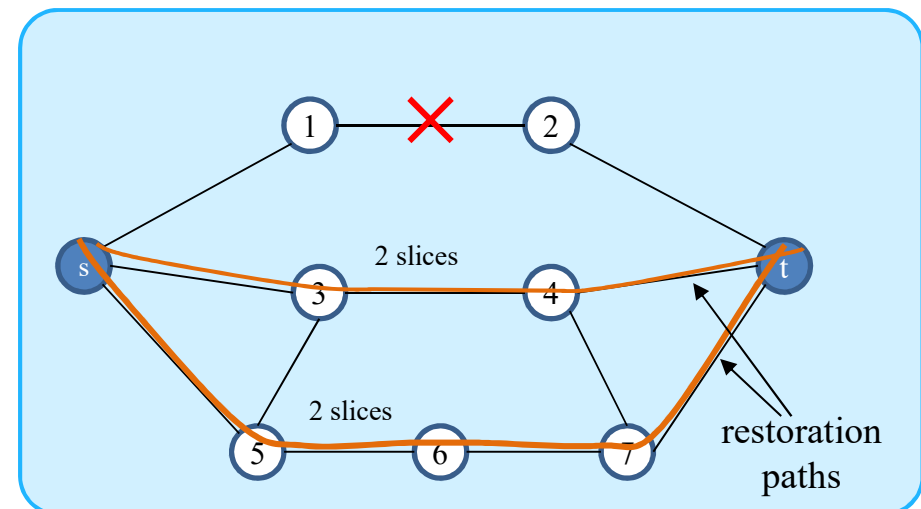
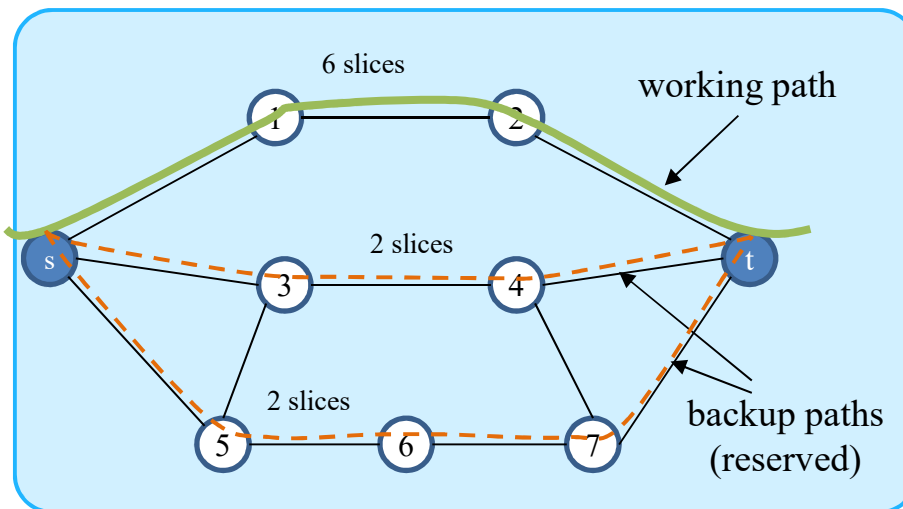
- Path computation for a set of connection requests.
 - the bulk of path requests is computed attaining the optimal solution for the whole set.
 - Increases optimality but increases also provisioning time.
- Bulk path computation can be used for restoration.
 - Reduces resource contention.
 - Increases resource utilization, specially in MLN.
 - Stringent computation times require heuristic algorithms.



* A. Castro et al., "Experimental Assessment of Bulk Path Restoration in Multi-layer Networks using PCE-based Global Concurrent Optimization," IEEE/OSA Journal of Lightwave Technology (JLT), vol. 32, pp. 81-90, 2014

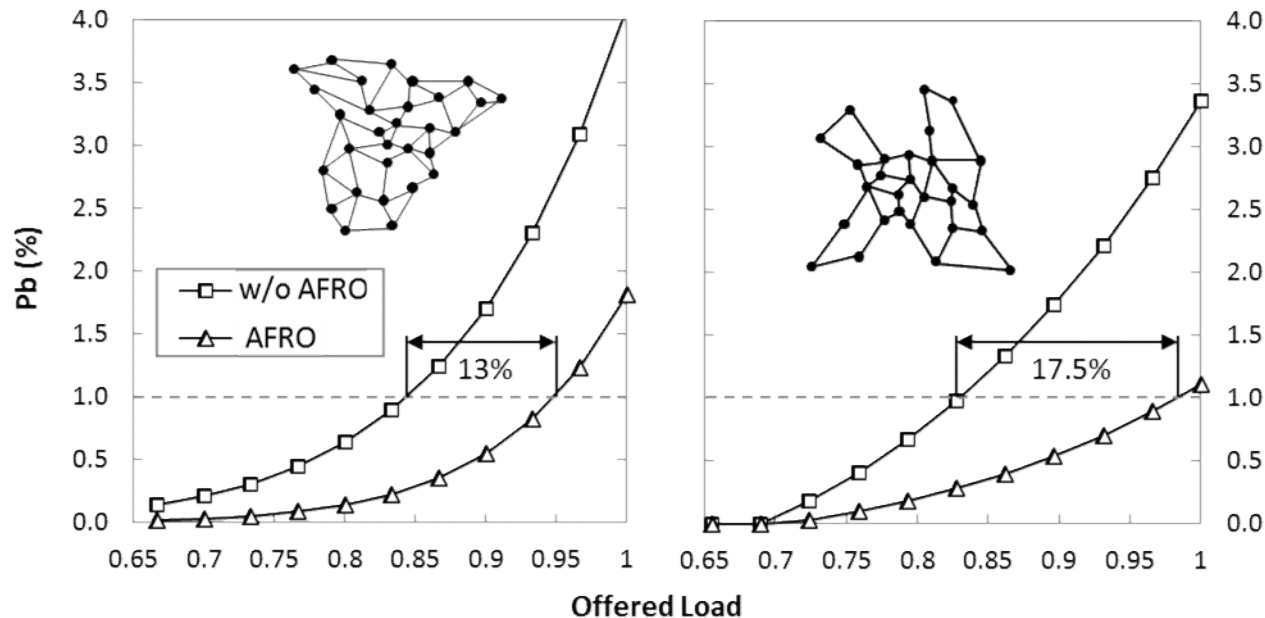
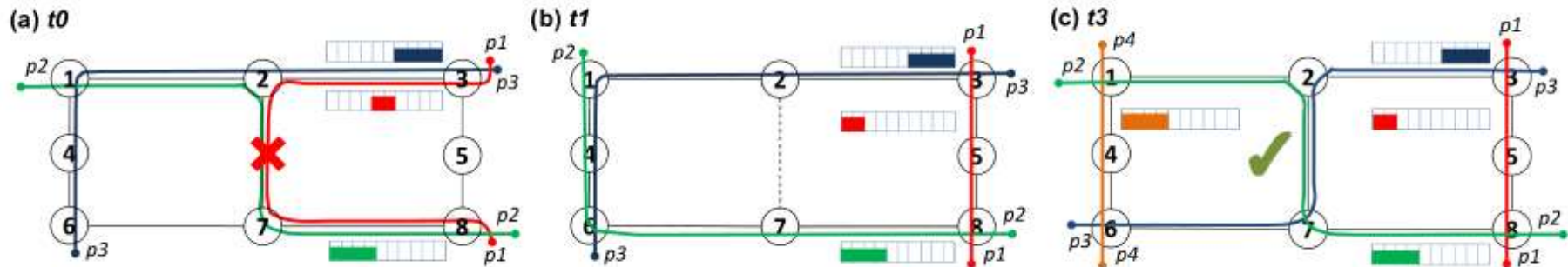
Bitrate Squeezed and Multi-path Recovery

Path Recovery	Description
Protection	Protection routes are known in advance: <ul style="list-style-type: none"> • Dedicated Protection • Shared Protection
Restoration	Restoration routes are found adaptively based on the failure and the state of the network at the time of failure.



* A. Castro et al., "On the benefits of Multi-path Recovery in Flexgrid Optical Networks," Springer Photonic Network Communications, vol. 28, pp. 251-263, 2014.

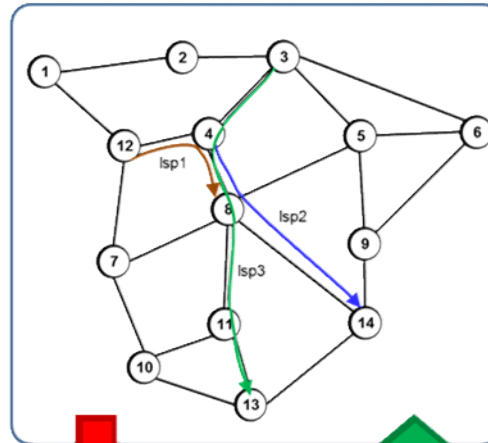
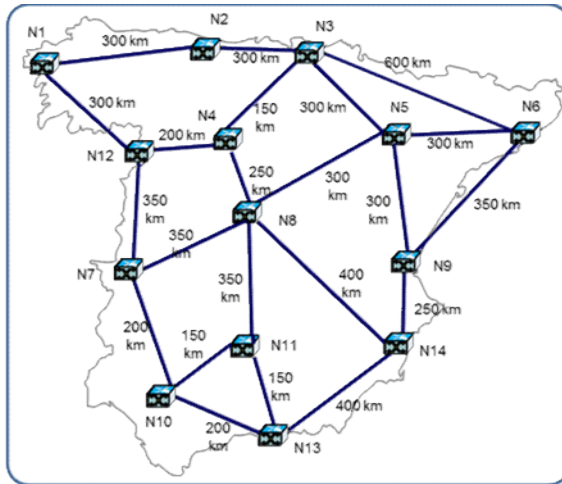
After Failure Repair Re-optimization (AFRO)



* M. Zotkiewicz et al., "Reoptimization of Dynamic Flexgrid Optical Networks After Link Failure Repairs," IEEE/OSA Journal of Optical Comm and Networking (JOCN), vol. 7, pp. 49-61, 2015.

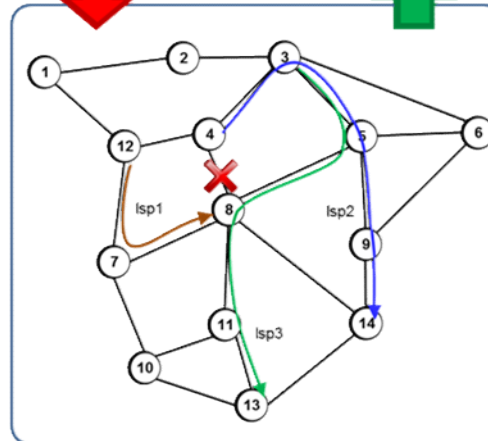
* Ll. Gifre et al., "First Experimental Assessment of ABNO-driven In-Operation Flexgrid Network Re-Optimization," IEEE/OSA Journal of Lightwave Technology (JLT), vol. 33, pp. 618-624, 2015.

Modulation Format-aware Restoration and Re-optimization



Before Failure				
LSP	BitRate (Gb/s)	Length (km)	Mod. Format	Slot Width (GHz)
lsp1	200	450	DP-QAM16	25
lsp2	400	650	DP-QAM16	50
lsp3	300	900	DP-QAM8	50

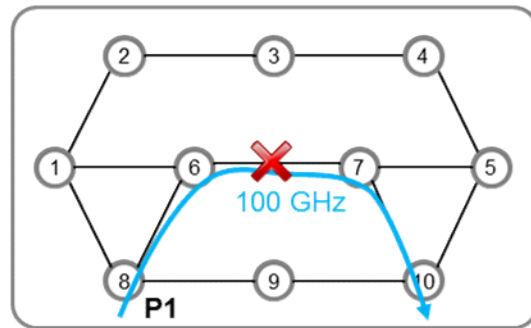
Mod. Format	Spectral Efficiency (bit/symbol)	Reach (km)
DP-QPSK	4	3000
DP-QAM8	6	1000
DP-QAM16	8	650



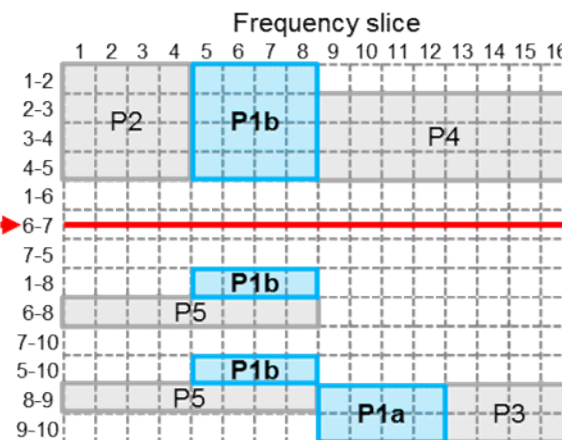
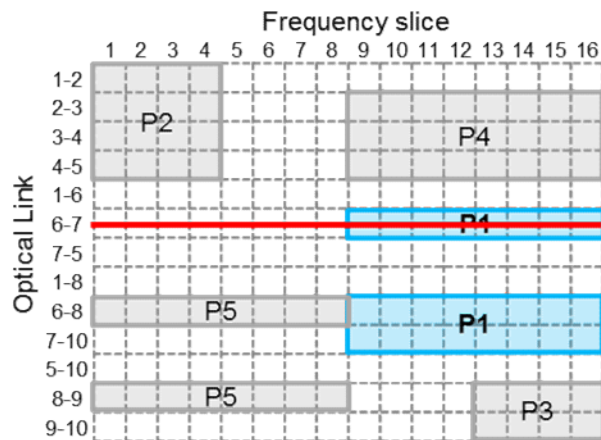
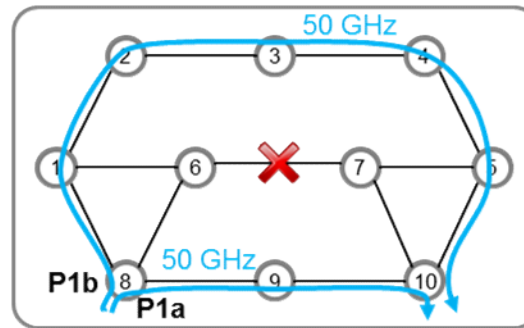
After Restoration				
LSP	BitRate (Gb/s)	Length (km)	Mod. Format	Slot Width (GHz)
lsp1	200	700	DP-QPSK	50
lsp2	300	1000	DP-QAM8	50
lsp3	100	1100	DP-QPSK	25

* LI. Gifre et al. "Modulation Format-aware Re-Optimization in Flexgrid Optical Networks: Concept and Experimental Assessment," in Proc. ECOC, 2015.

SBVTs under dynamic traffic

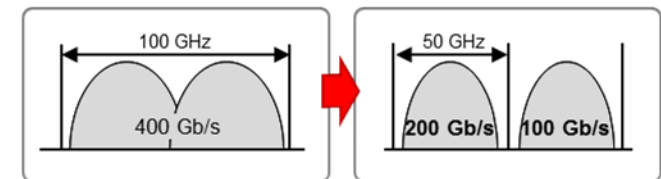


Restoration

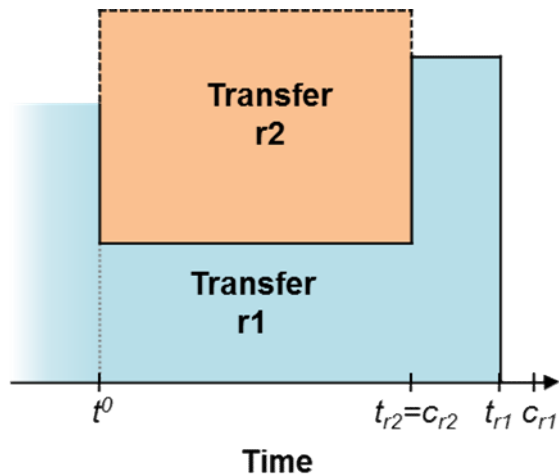
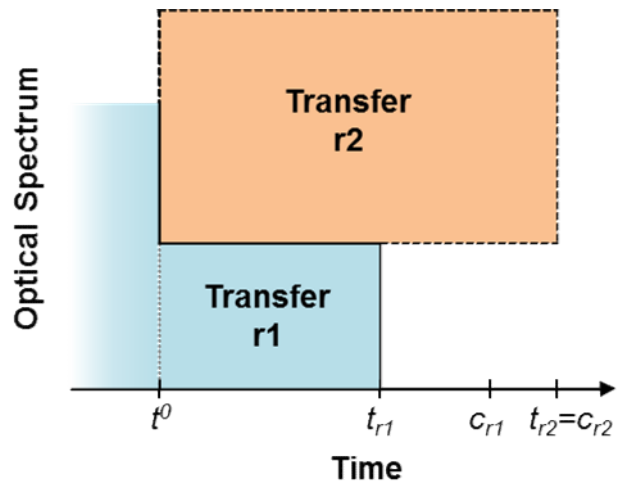


Mod. Format	bits/symbol	Reach
DP-QPSK	4	3000 Km
DP-QAM8	6	1000 Km
DP-QAM16	8	650 Km

Path Id	Bitrate (Gb/s)	Len. (Km)	Mod. Format	Slot Width
P1	400	550	DP-QAM16	100 GHz
P1a	200	300	DP-QAM16	50 GHz
P1b	100	1250	DP-QPSK	50 GHz



Routing and Scheduled Spectrum Allocation (RSSA)



Given:

- a network topology represented by a graph $G(L, E)$, being L the set of locations and E the set of fiber links connecting two locations;
- a subset $D \subseteq L$ with those locations source of transfer-mode traffic (datacenters);
- a subset $U \subseteq L$ with those locations source of fixed-bitrate traffic;
- the characteristics of the spectrum for each link in E : a set S of available spectrum slices of a given spectrum width;
- the characteristics (capacity and number of flows) of the optical transponders equipped in each location;
- a set R with the transferences currently in progress in the network. For each transference $r \in R$, the tuple $\{o_r, d_r, v_r, c_r, r_r, s_r^0, s_r^l, t_r^l, t_r\}$ specifies the origin (o_r) and destination (d_r) datacenters, the remaining amount of data (v_r) to be transferred, the requested completion time (c_r), the route (r_r) and slot currently allocated (s_r^0), the scheduled slot allocation (s_r^l) to be performed at time t_r^l , and the scheduled completion time (t_r);
- the new transfer-mode request, described by the tuple $\{o_r, d_r, v_r, c_r\}$. Let t^0 denote the current time.

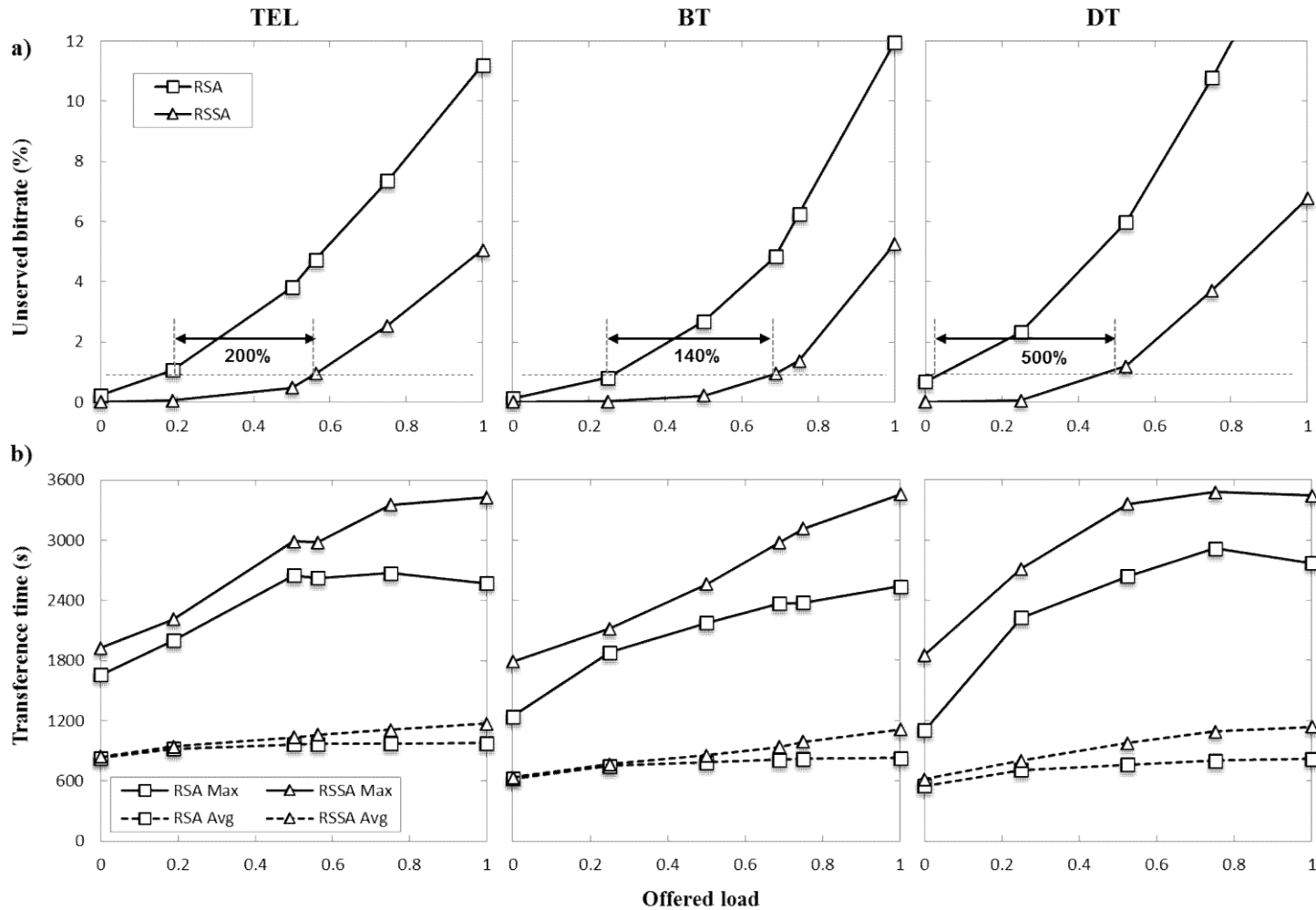
Output:

- the route (r_r), the slot allocation (s_r^0) and the scheduled completion time (t_r) for the new transference request. The bitrate of the connection is given by $b(s_r^0, l(r_r))$, where $l(r_r)$ returns the total length of the route r_r .
- the new spectrum allocation (w_r^0), scheduled reallocation (w_r^l, t_r^l) and completion time (t_r) for each transference request to be re-scheduled.

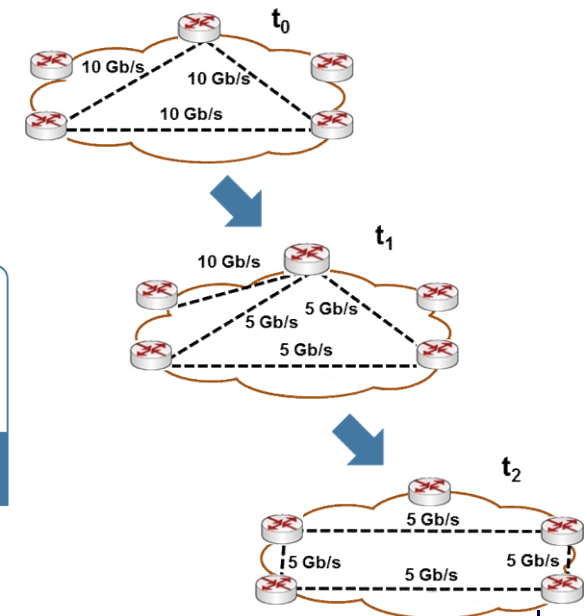
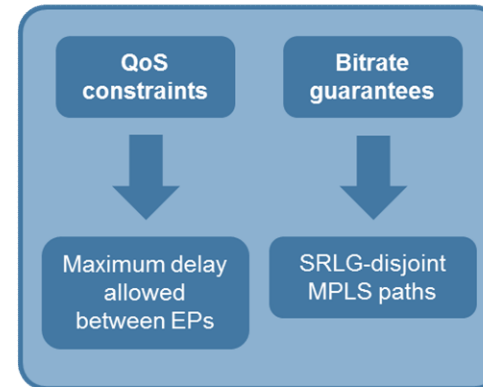
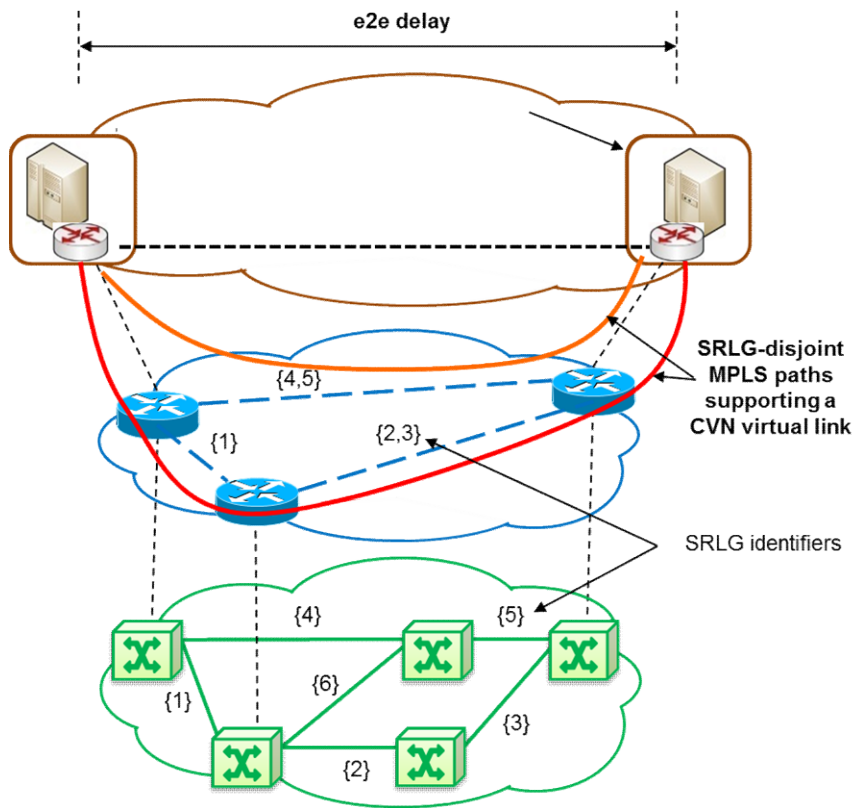
Objective: Minimize the number of connections to be re-scheduled to make room for the incoming request.

* A. Asensio and L. Velasco, "Managing Transfer-based Datacenter Connections," IEEE/OSA Journal of Optical Communications and Networking (JOCN), vol. 6, pp. 660-669, 2014.

Results



CVN Provisioning with QoS Constraints and Bitrate Guarantees



Gb/s	EP1	EP2	EP3
EP1	-	0	60
EP2	0	-	80
EP3	60	80	-

Capacity matrix

ms	EP1	EP2	EP3
EP1	-	0	10
EP2	0	-	10
EP3	10	10	-

Quality of Service (QoS)

Gb/s	EP1	EP2	EP3
EP1	-	0	30
EP2	0	-	40
EP3	30	40	-

Bitrate guarantees



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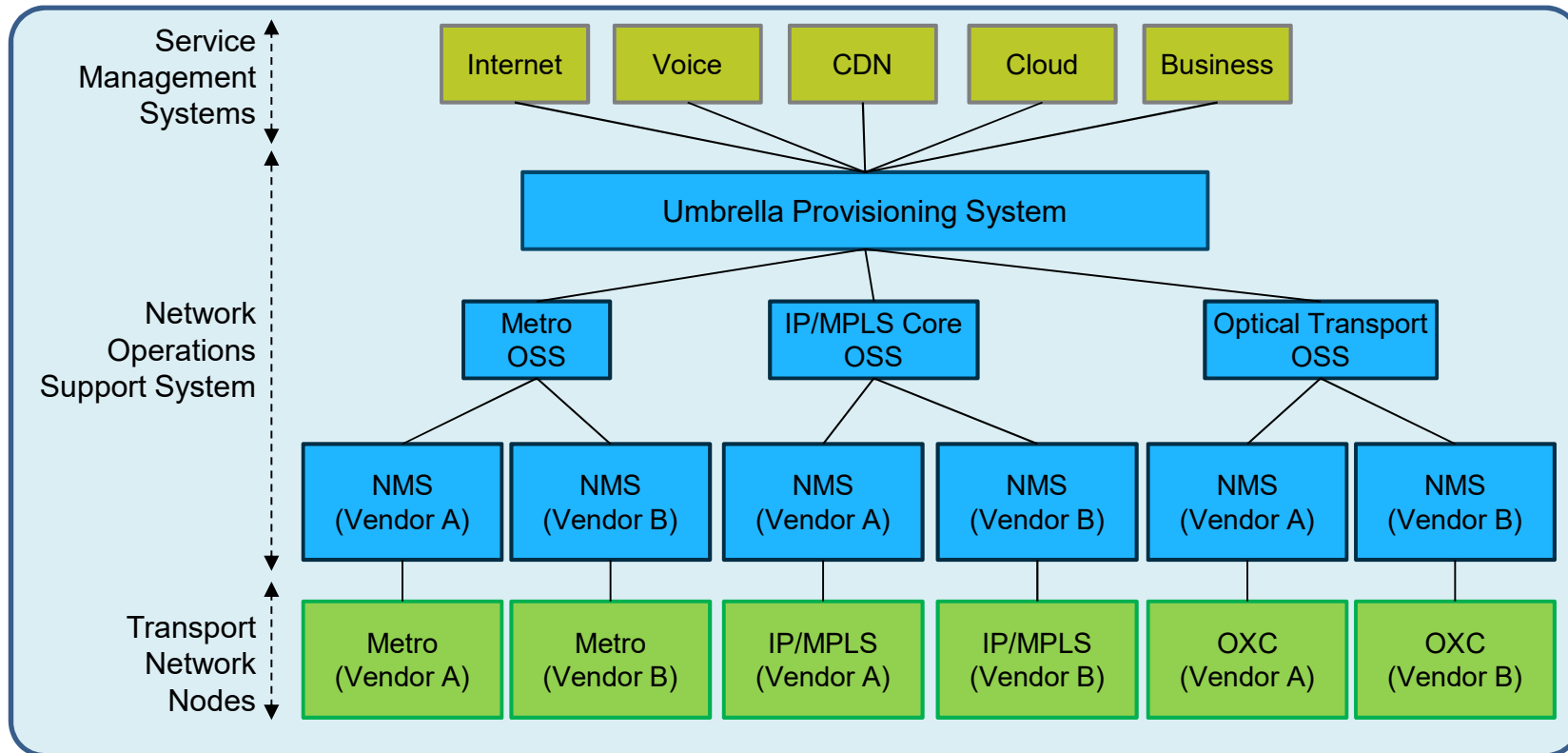


Part IV

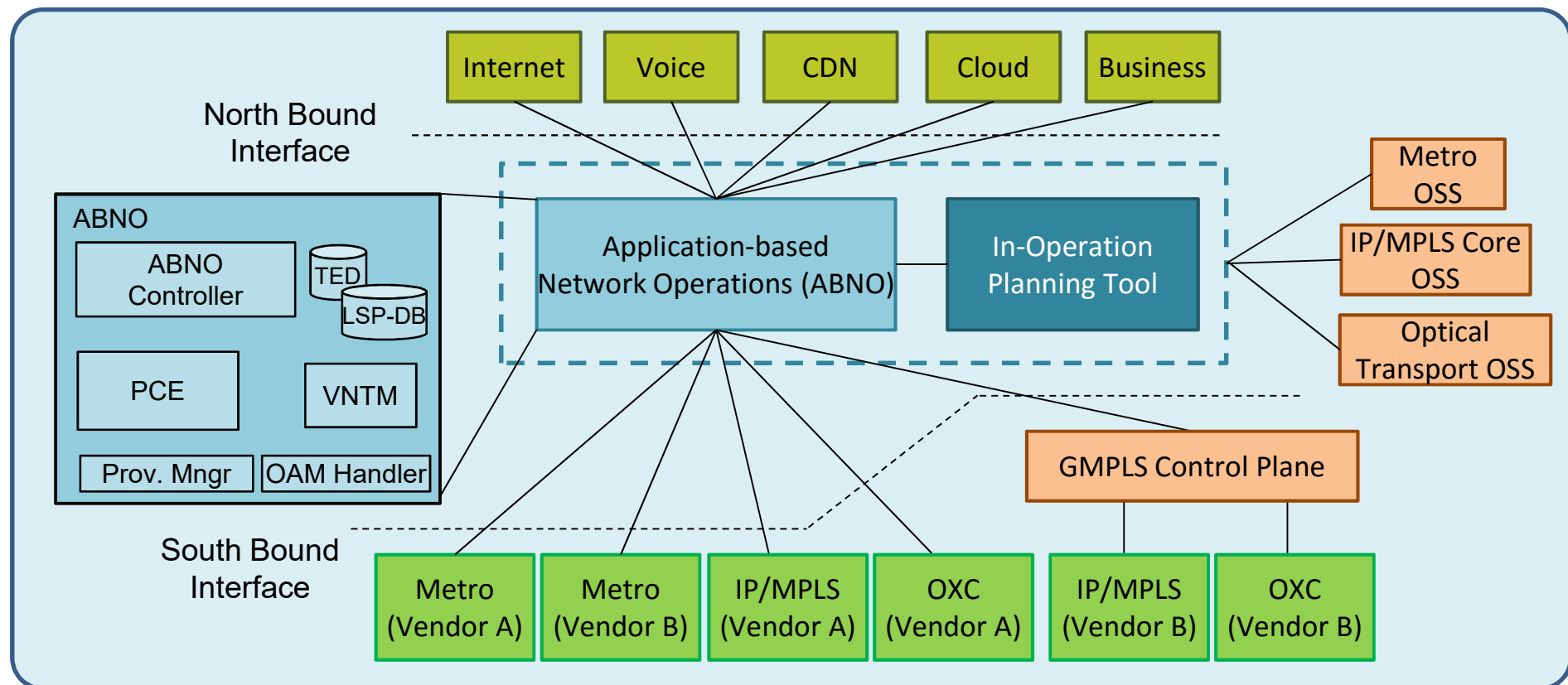
Extending networks life-cycle

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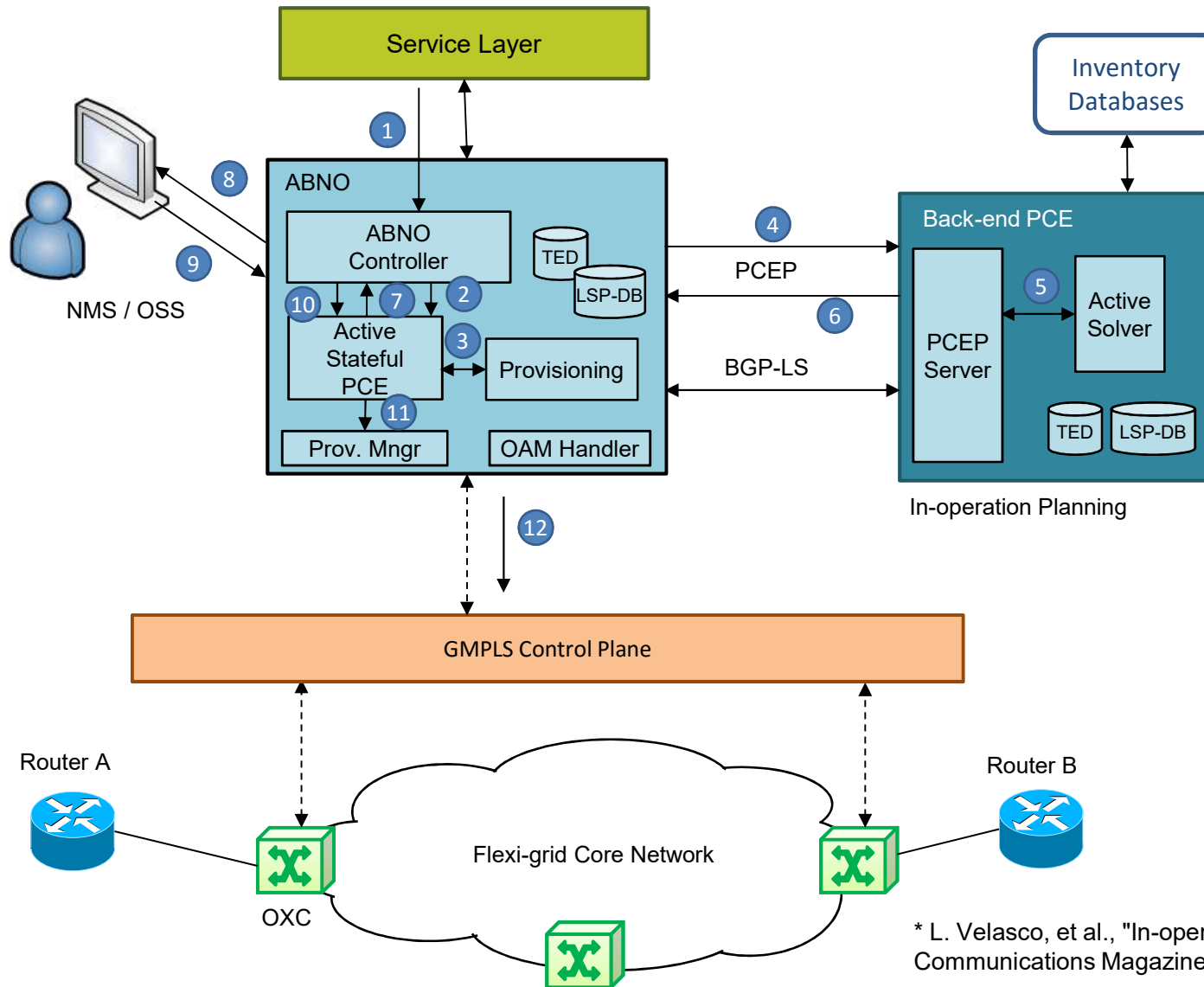
Static Network Operation



Migration towards in-operation network planning

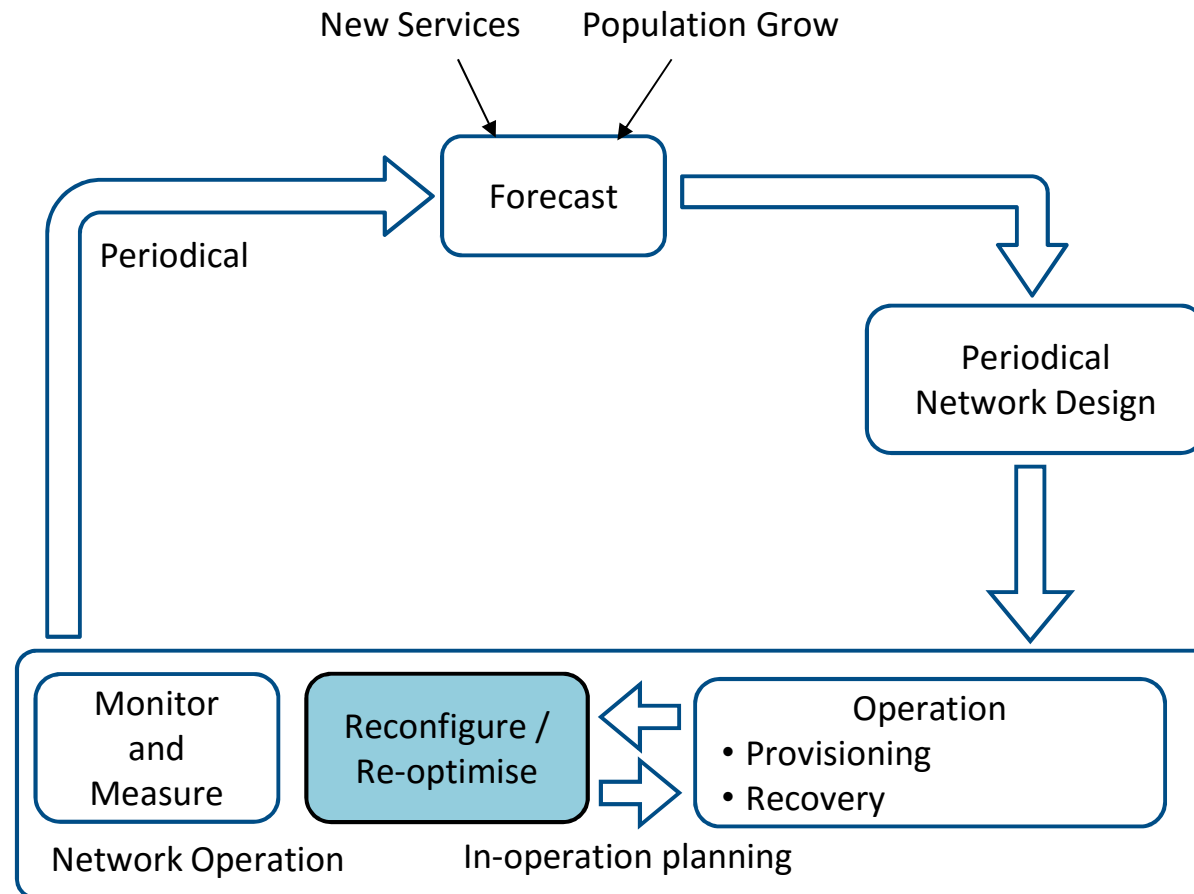


Re-optimisation Process

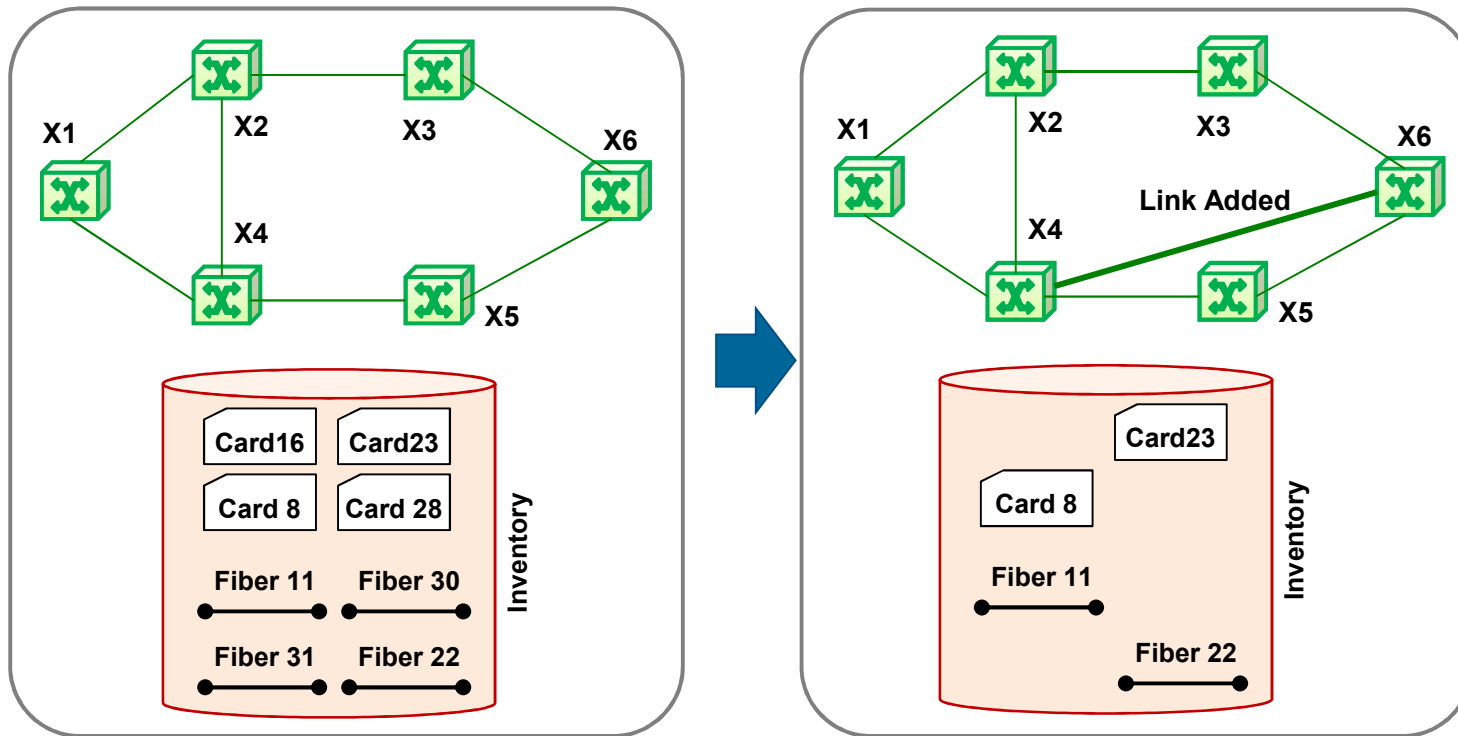


* L. Velasco, et al., "In-operation Network Planning," IEEE Communications Magazine, vol. 52, pp. 52-60, 2014.

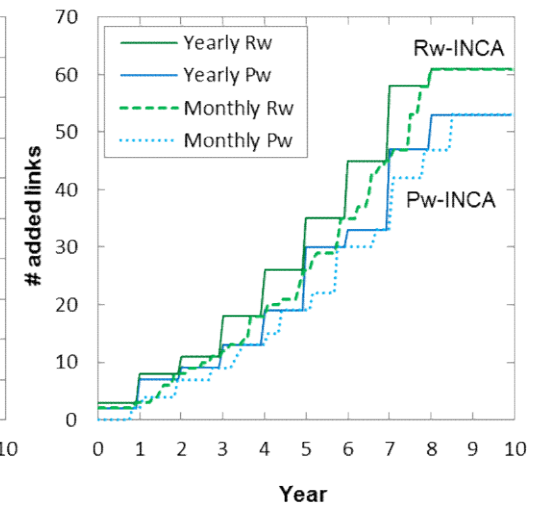
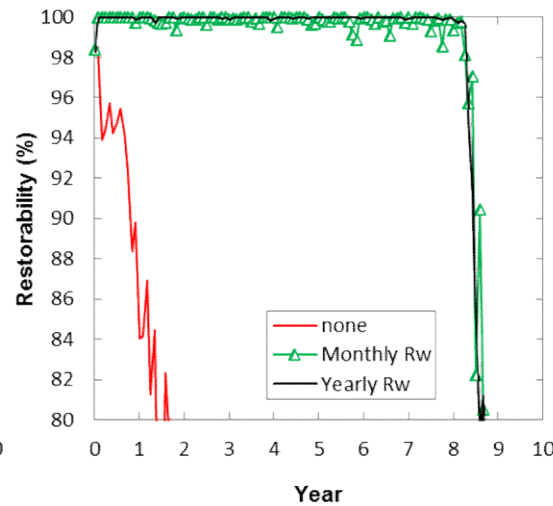
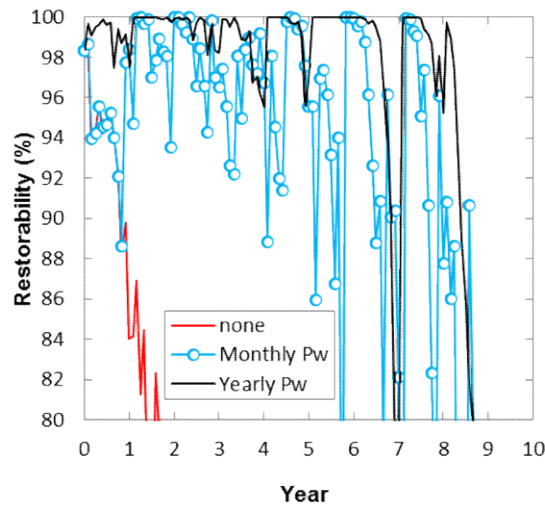
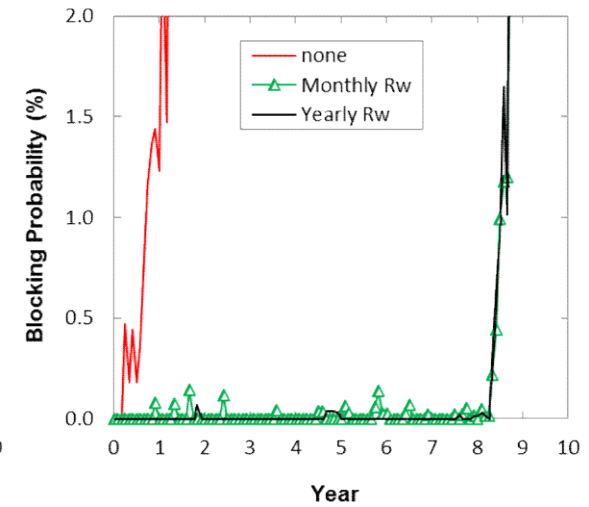
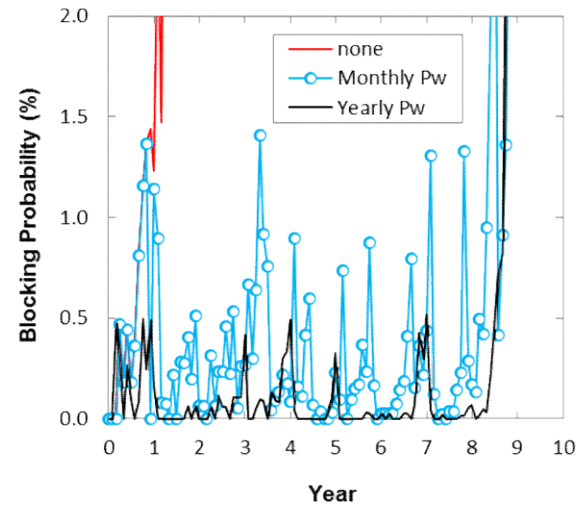
In-operation Planning



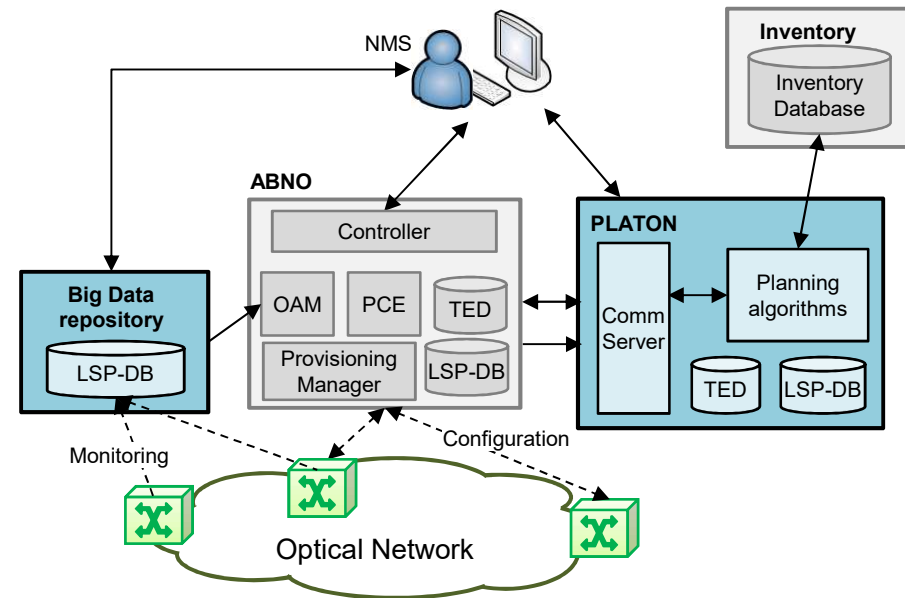
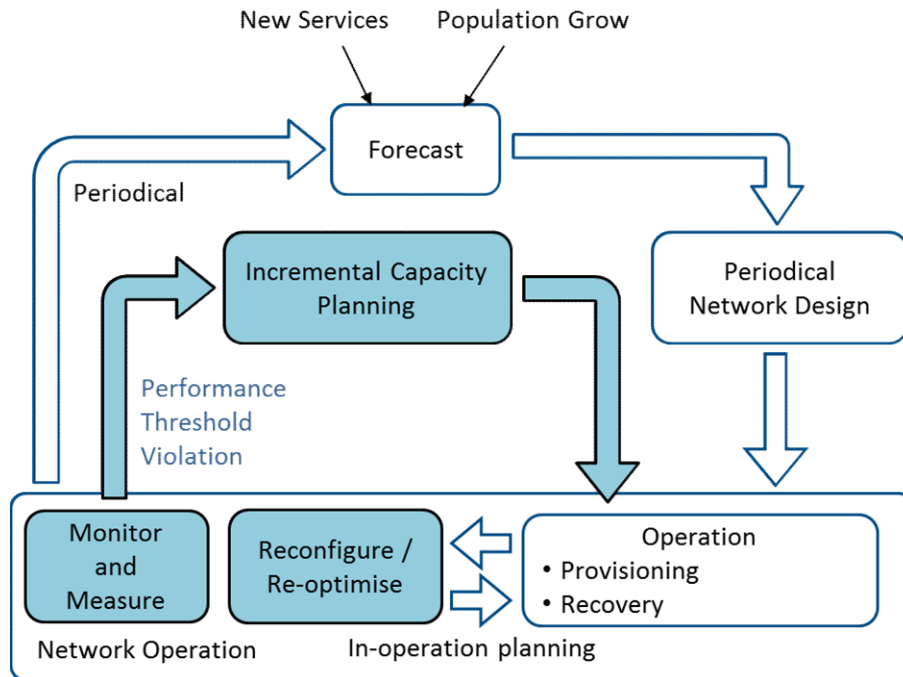
Incremental Planning



Results



Extended Networks Life Cycle



* L. Velasco et al., "On-demand Incremental Capacity Planning in Optical Transport Networks," IEEE/OSA Journal of Optical Communications and Networking (JOCN), vol. 8, pp. 11-22, 2016.



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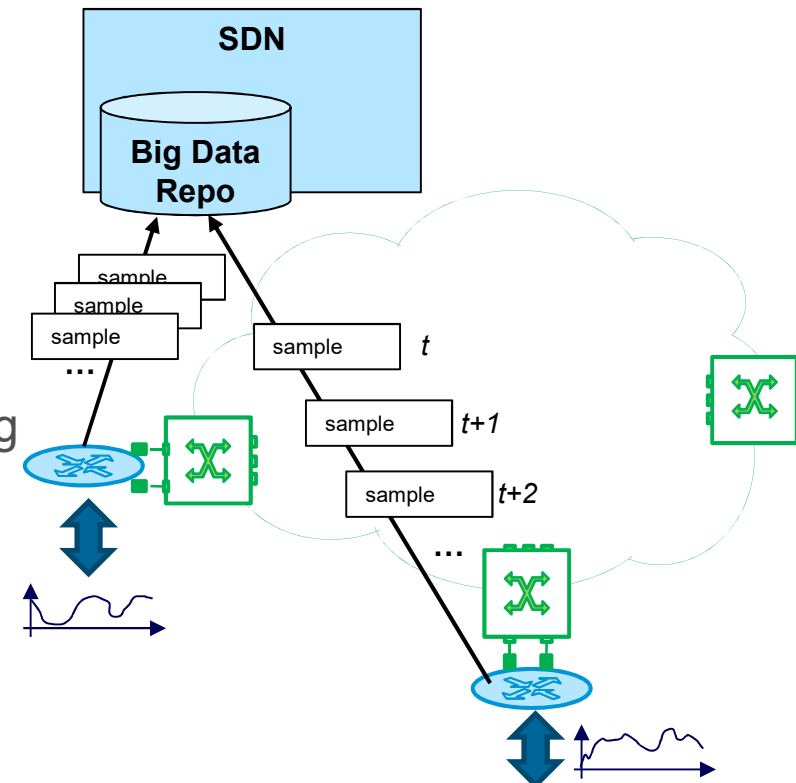
Part V

Towards Cognitive Networking

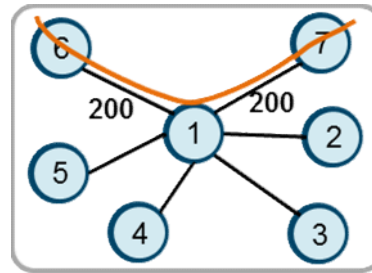
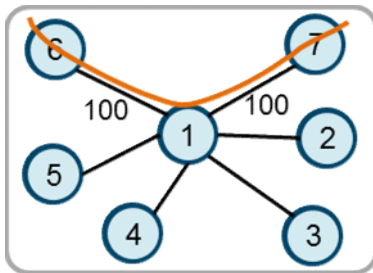
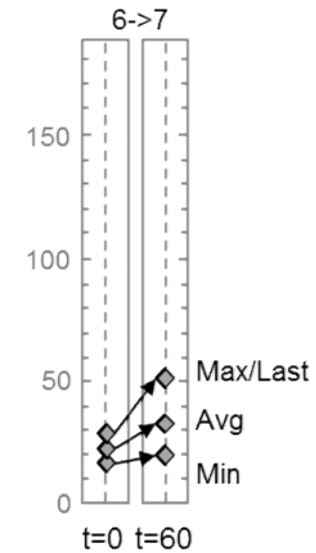
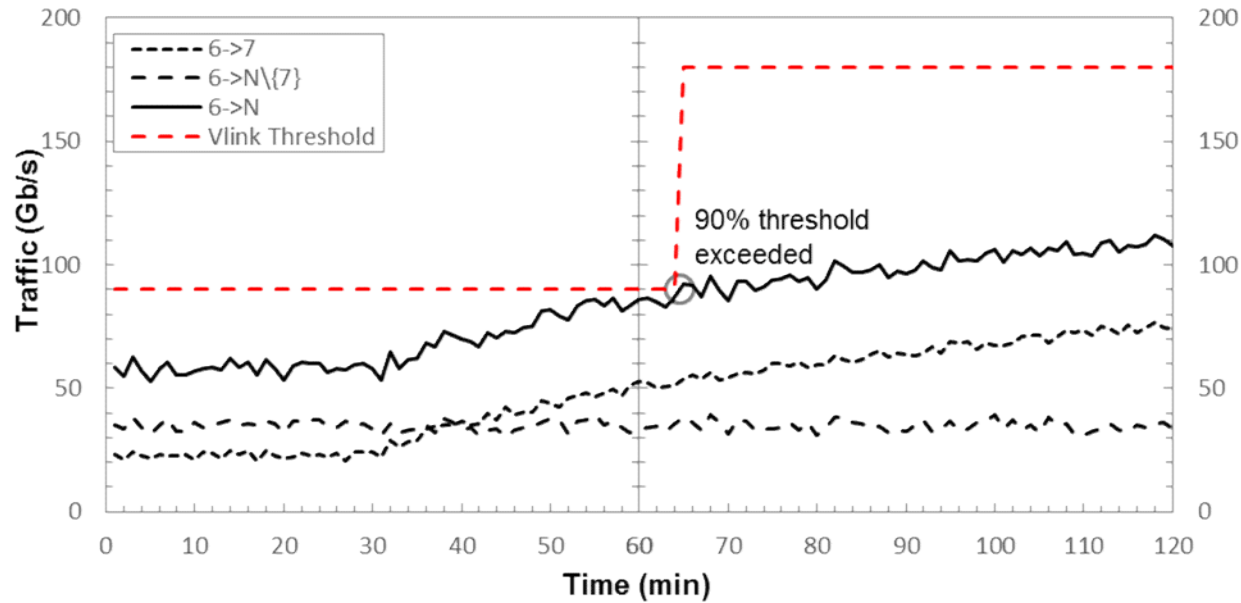
Luis Velasco

Source-destination traffic analysis

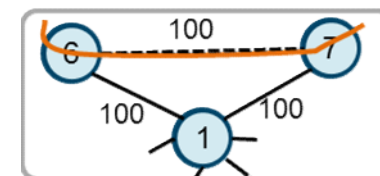
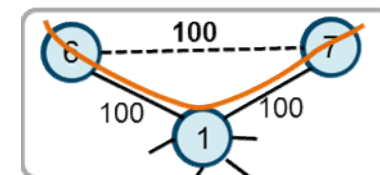
- Data collected from packet nodes
 - Every L2/L3 node generates a sample of monitored data every fixed time interval (e.g. 5 min)
 - Sample = traffic sent from this source to every destination
- Huge amount of monitored data samples
 - Pre-processing and modelling is necessary
 - Data stream mining -> Sketches
 - ML and Statistics -> Models
- Applications for network optimization
 - Traffic prediction-based in-operation planning
 - Model-triggered network re-optimization



VNT reconfiguration

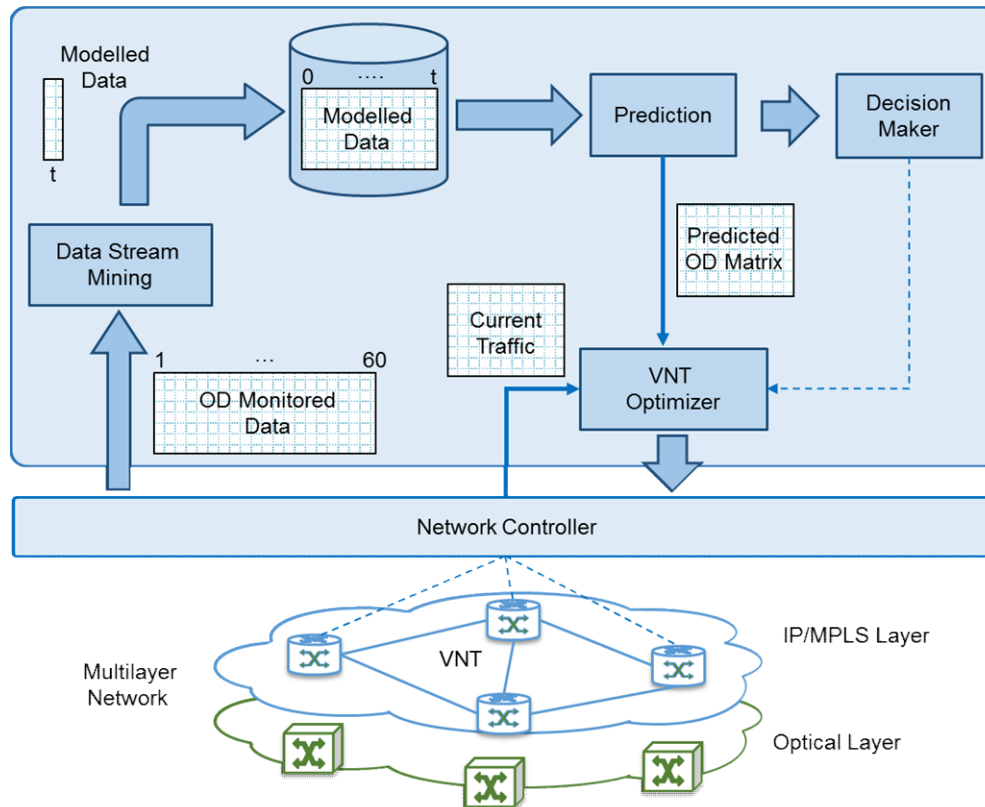


Threshold-based



Analytics-based

VNT reconfiguration based on traffic prediction problem



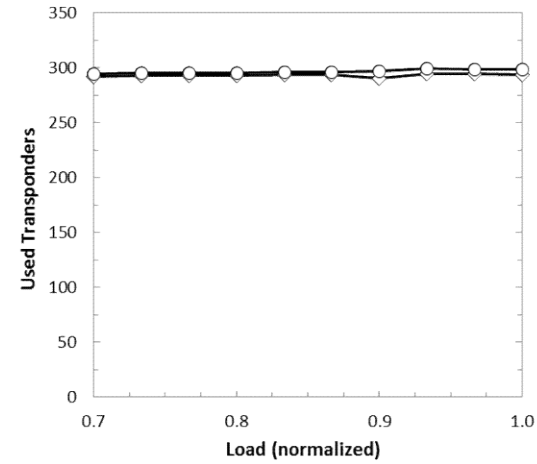
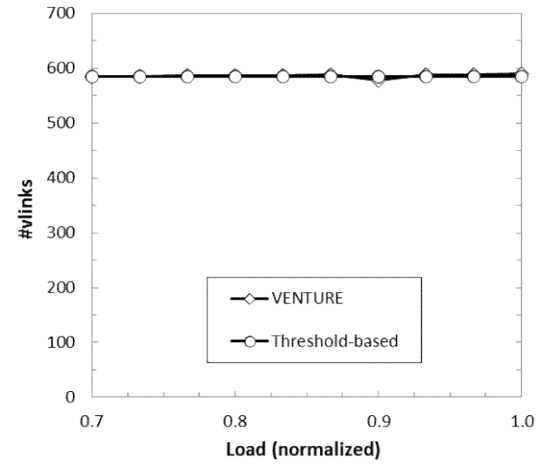
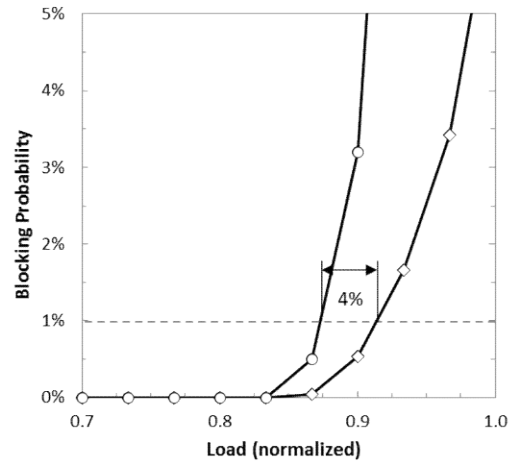
Given:

- An optical network represented by graph $G_O(N, L)$, being N the set of OXC nodes and L the set of fiber links.
- The current VNT represented by graph $G_V(V, E')$, being $V \subseteq N$ the subset of IP/MPLS routers and $E' \subseteq E$ the subset of current vlinks. Set E is the set of all possible vlinks among the IP/MPLS nodes.
- The set P of current lightpaths supporting E' .
- The set and the capacity $Q(v)$ of available transponders for each node v in V .
- The set D of demands currently set-up, specifying source, destination, and requested bitrate.
- The **predicted OD traffic matrix** specifying the predicted bitrate.
- The maximum number k of new vlinks to be added to the VNT.

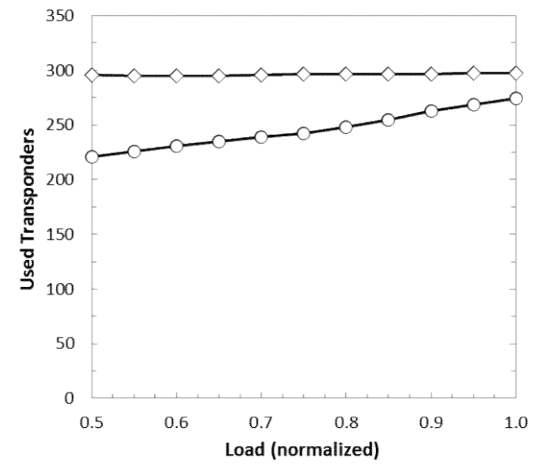
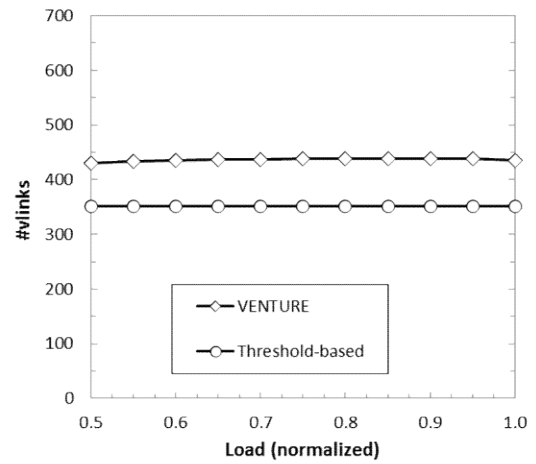
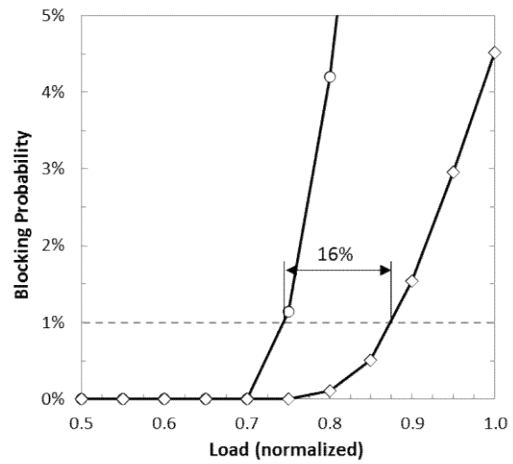
Find: a reconfigured VNT $G_V^*(V, E^*)$, where $E^* \subseteq E$, and a set $P^* \supseteq P$ of lightpaths supporting E^* .

Objective: Minimize the overall resource utilization to serve both, D and OD sets.

Results

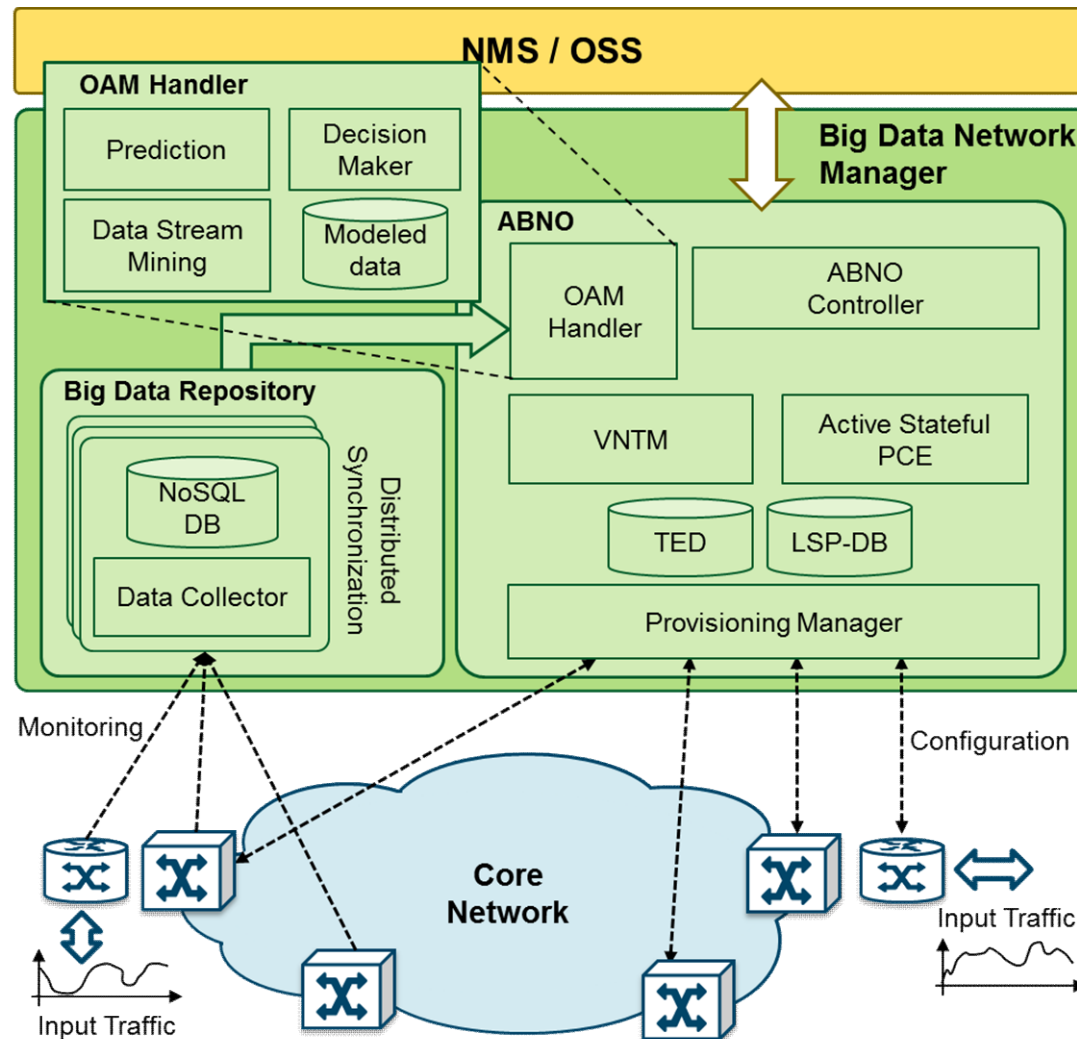


Non-directional Traffic



Directional Traffic

Big data network manager architecture



Conclusions

- **Basic RSA-based problems have been reviewed**
- **Off-line planning:**
 - Examples for national IP/MPLS Networks and for gradual migration process from fixed to Flexgrid has been presented.
- **Re-optimization** can be performed to increase network performance.
 - Examples included defragmentation and after failure repair optimization
- **In-operation** planning and **holistic** planning extended the networks life-cycle.
- **Data analytics** were introduced as a way to add cognition to the network.



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Thank you for your attention!

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March, 2016