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Solving Routing and Spectrum Allocation Related Optimization Problems

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- I. RSA Basics**
- II. Solving Techniques**
- III. Advanced RSA**
- IV. Off-line Network Planning**
- V. In-operation Network Planning**



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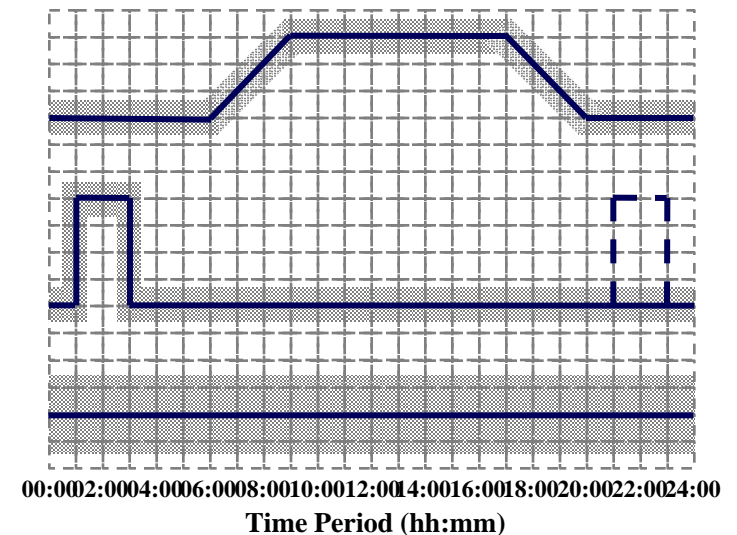
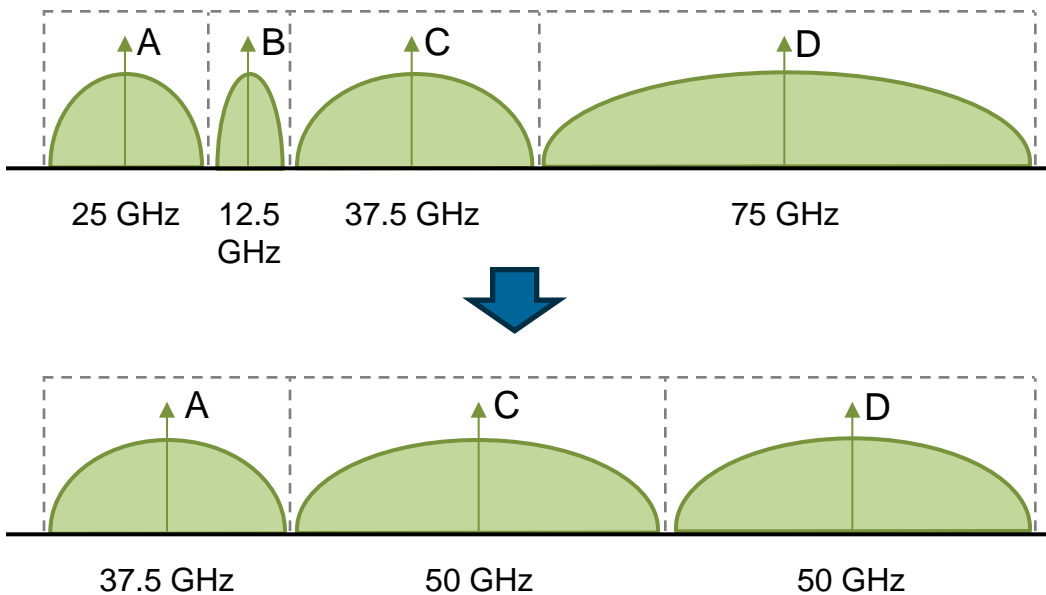
Part I

RSA basics

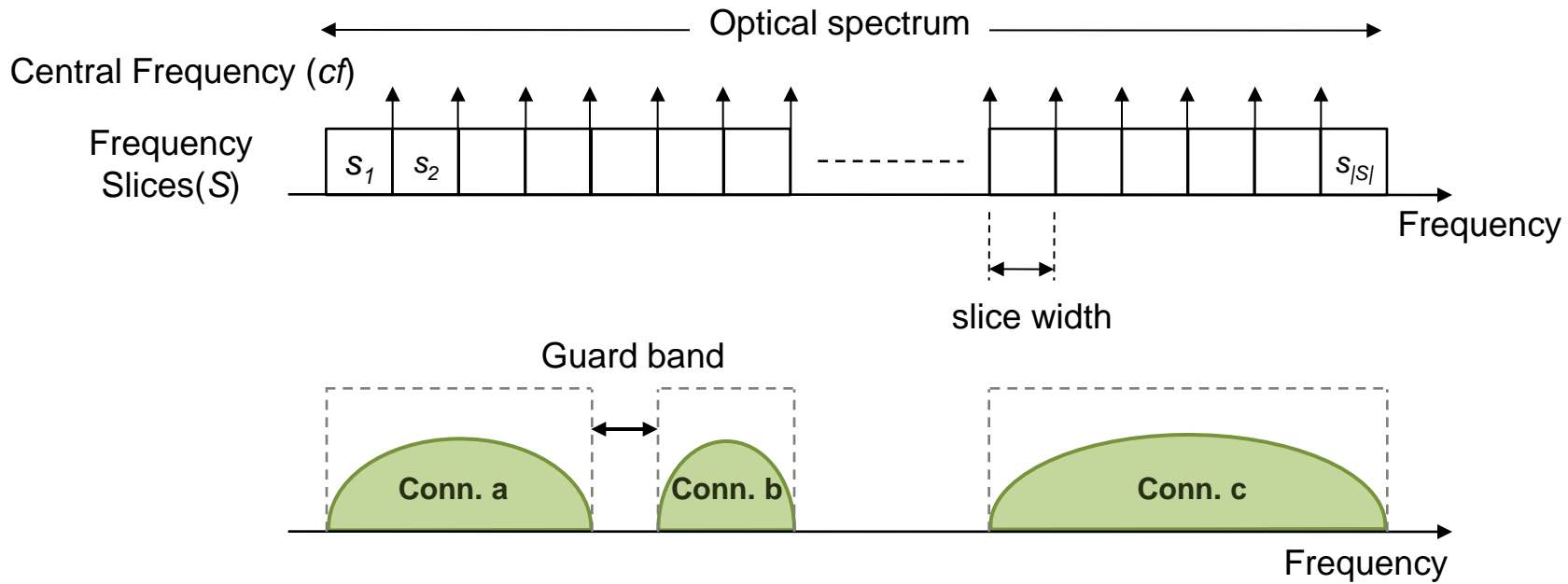
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Flexgrid

- Flexgrid uses a finer spectrum granularity.
 - The optical spectrum is divided into frequency slices (e.g. 6.25GHz).
- 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.



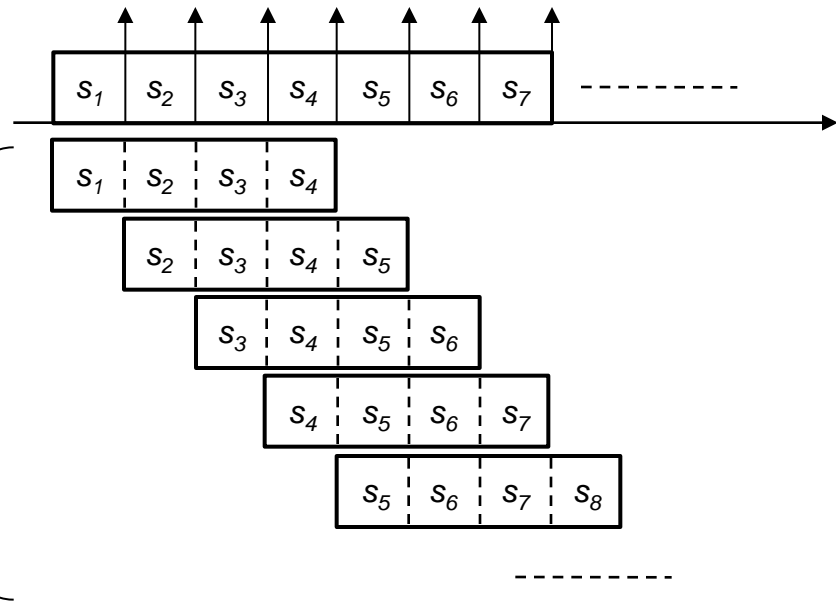
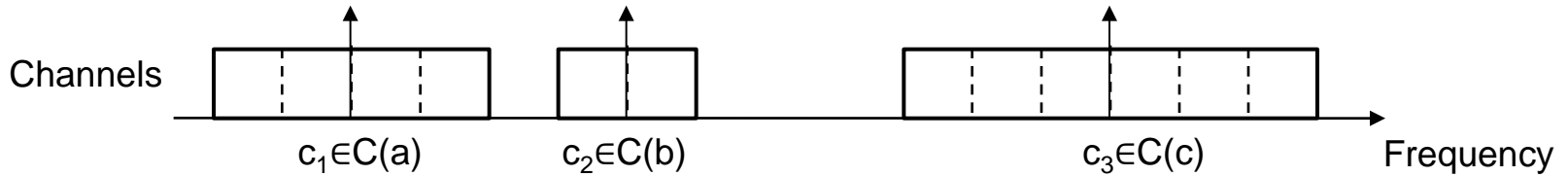
Spectrum allocation



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 Channels



$C(d)$ 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 $C(d)$

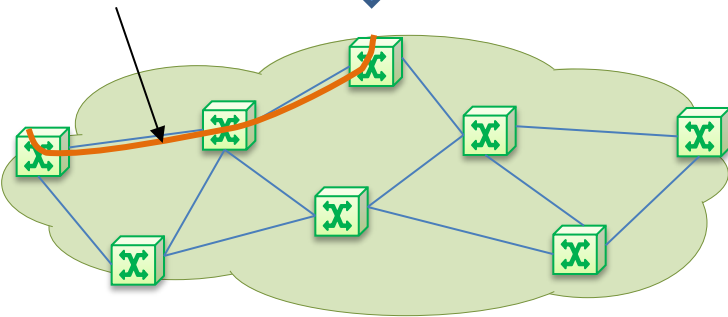
Basic RSA Problem Statement

Demand Matrix

From	To	BW



Lightpaths



Flexgrid

- Given:
 1. a set N of locations and a set of optical fibers E connecting those locations;
 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 Channel Assignment Formulation

Pre-computed Parameters

- $P(d)$ Set of predefined candidate paths for demand d .
- $C(d)$ Set of channels for demand d .
- δ_{pe} Equal to 1 if path p uses link e , 0 otherwise.
- γ_{cs} Equal to 1 if channel 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 channel c is assigned to path p and 0 otherwise

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

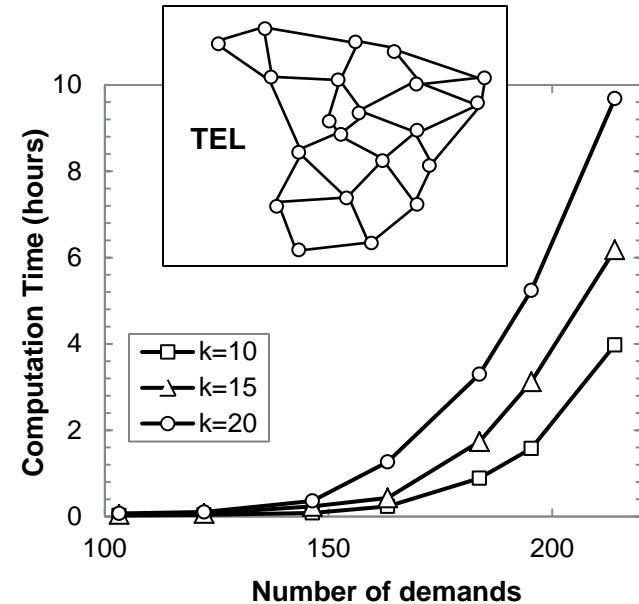
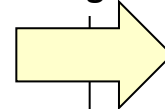
$O(|P(d)| \cdot |D| \cdot |C|)$ variables
 $O(|D| + |E| \cdot |S|)$ constraints

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., "Modeling the Routing and Spectrum Allocation Problem for Flexgrid Optical Networks," Springer Photonic Network Communications, 24, 177-186, 2012

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;
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 CA Formulation

Variables

- w_{dec} Binary. Equal to 1 if demand d uses channel 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:

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

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

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

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

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

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

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

* L. Velasco, et al., "Modeling the Routing and Spectrum Allocation Problem for Flexgrid Optical Networks," Springer Photonic Network Communications, 24, 177-186, 2012

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

Solving Techniques

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Heuristics

- RSA problems are *NP-hard*, so there is little hope of ever finding efficient exact solution procedures for them.
- Un-tractability of MILP formulations appears when instances to be solved involve a large number of variables.
 - Tens of nodes x Tens of links x Hundreds of slots x Hundreds of demands = Millions of binary variables.
- Heuristics, i.e., **approximate solution techniques**, can be used to tackle RSA-based (combinatorial) problems.

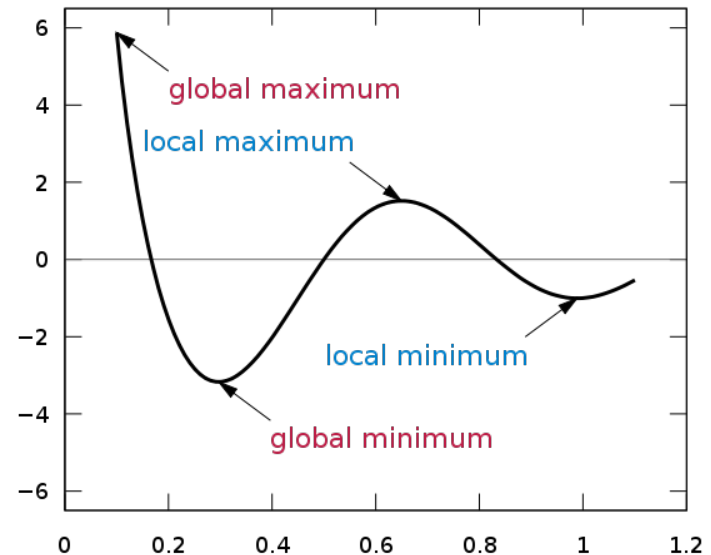
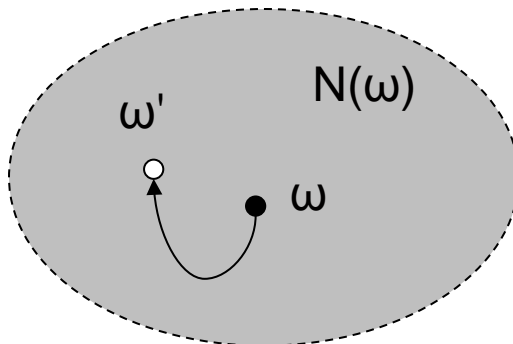
Ω Solution space

$f: \Omega \rightarrow \mathbb{R}$ Objective function defined on the solution space

goal: find $\omega^* \in \Omega, f(\omega) \geq f(\omega^*) \forall \omega \in \Omega$

Heuristics

- Heuristic algorithms usually consists on two phases:
 - Constructive Phase, where a solution is built.
 - Local search, where the solution is improved.
- During the **Constructive phase**, greedy algorithms may be used.
- During the **local search** phase, exchanges among elements in the solution and not in the solution are done.

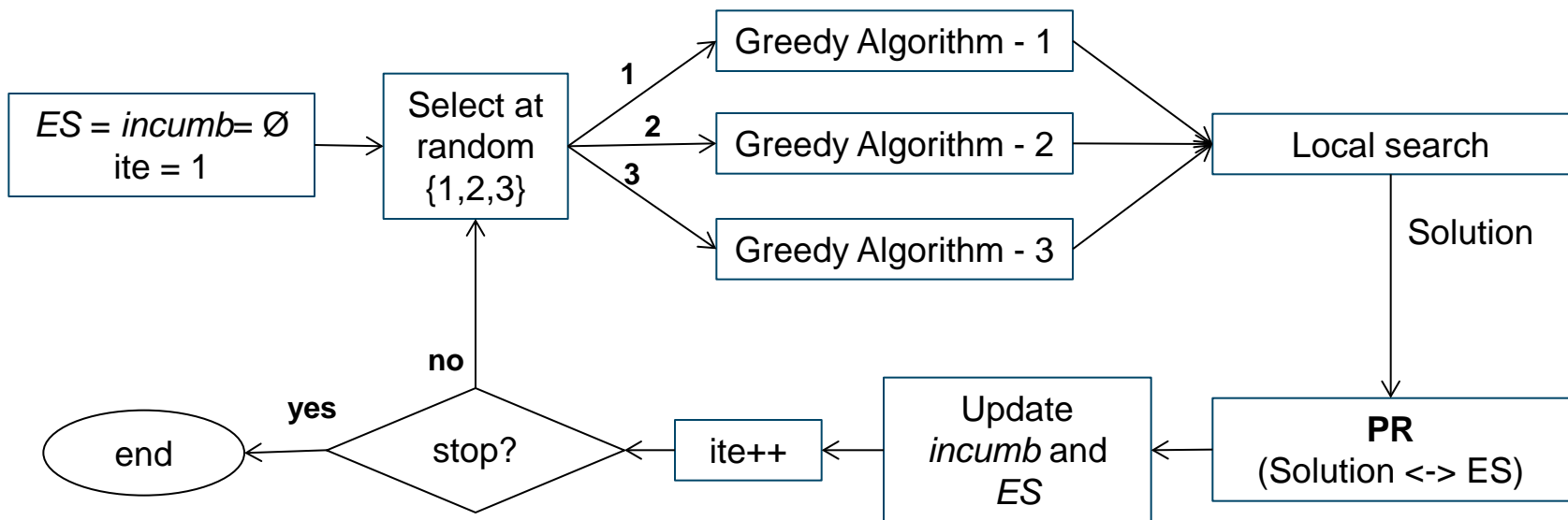


Meta-heuristics

- Meta-heuristics allow go beyond heuristics by:
 - adding variability (randomize)
 - allowing escaping from local optima, at risk of cycling
- Some well-known meta-heuristics are:
 - **GRASP** (Feo and Resende): a multi-start metaheuristic for combinatorial problems.
 - Evolutionary algorithms (genetics). **BRKGA** (M. Resende)
 - **Simulated Annealing**, probabilistic metaheuristic often used when the search space is discrete
 - **Tabu Search** (Fred W. Glover): Enhances the performance of Local search by using memory structures.
 - **Ant colony**: probabilistic technique (Marco Dorigo)
 - **Path relinking**: an *intensification* method.

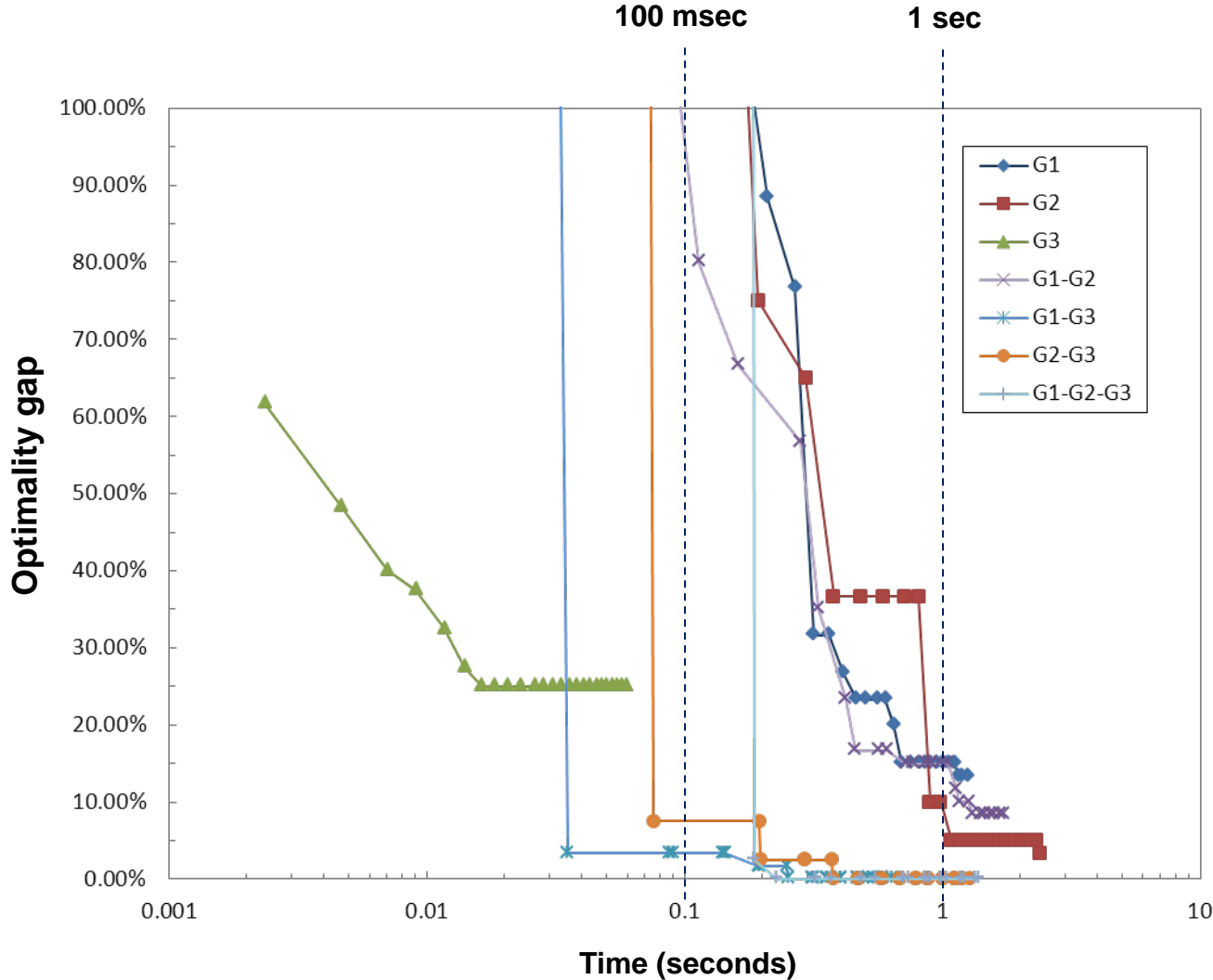
Hybrid meta-heuristics

- Heuristic hybridization: Combine several of the previous techniques.
 - GRASP + PR -> Diversification + Intensification
- Example: multi-greedy + PR
 - **Three different constructive** algorithms to provide diversification.
 - **Path Relinking** finds new solutions in the path connecting two solutions.



* M. Ruiz, et al., "Ultra-fast meta-heuristic for the spectrum re-allocation problem in flexgrid optical networks", 25th European Conference on Operational Research (EURO XXV), 2012

Hybrid meta-heuristics: Solving Time



G3 provides feasible solutions in few milliseconds (20-50 msec)

G1 and G2 provide better solutions but at the expense of higher computation time

Multi-start with PR provides the best results:
 (G1 + G3)
 (G2 + G3)
 (G1 + G2 + G3)

Large Scale Optimization (LSO)

- The objective of LSO methods is to extend the exact methodology (Branch & Bound) for MILP formulations.
- Among different methods, decomposition methods have been successfully used for solving communications network design problems
 - **Lagrangian relaxation** aims at improving lower bounds on the objective function, a decisive factor for the effectiveness of Branch & Bound.
 - **Column generation** consists in finding a reduced set of variables (columns) to solve the linear relaxation of the link-path MILP formulations, providing high quality integer solutions in an efficient way.
 - **Benders decomposition** is an iterative procedure based on projecting out a subset of variables from the original problem with the whole set of variables and creating new constraints (cuts) from the projected ones.

Lagrangian Relaxation

- Some (*difficult*) constraints are moved to the objective function and penalized by **Lagrange multipliers** (λ)

$$\begin{array}{ll}
 \min & \sum_{d \in D} x_d \cdot b_d \\
 \text{s.t.} & \\
 & \sum_{p \in P(d)} \sum_{c \in C(d)} y_{pc} + x_d = 1 \quad \forall d \in D \\
 & \boxed{\sum_{d \in D} \sum_{p \in P(d)} \sum_{c \in C(d)} \gamma_{cs} \cdot \delta_{pe} \cdot y_{pc} \leq 1} \quad \forall e \in E, s \in S
 \end{array}$$

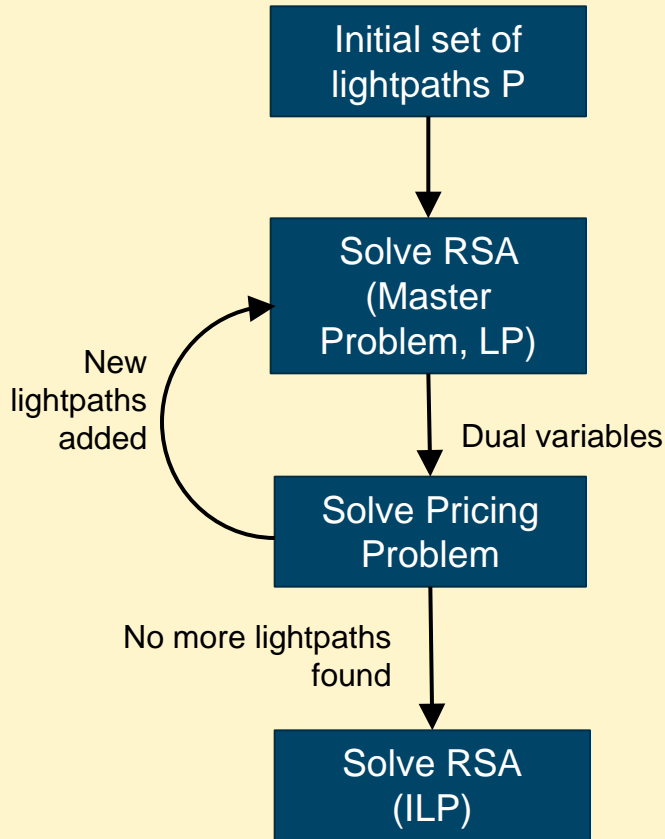


$$\begin{array}{ll}
 \min & \sum_{d \in D} x_d \cdot b_d + \boxed{\sum_{e \in E} \sum_{s \in S} \lambda_{es} \cdot \left(\sum_{d \in D} \sum_{p \in P(d)} \sum_{c \in C(d)} \gamma_{cs} \cdot \delta_{pe} \cdot y_{pc} - 1 \right)} \\
 \text{s.t.} & \\
 & \sum_{p \in P(d)} \sum_{c \in C(d)} y_{pc} + x_d = 1 \quad \forall d \in D
 \end{array}$$

- It allows obtaining **lower bounds** for the original problem for any positive Lagrange multipliers.
- Those Lagrange multipliers that provide the optimal solution of the original problem can be found by **solving the Lagrangian dual problem**.
 - Iterative methods such as **sub-gradient optimization** methods are commonly used for solving the Lagrangian dual problem.

Column Generation Algorithm

Main Algorithm



Lightpath set initialization

For each demand d :

- 1) Compute the shortest (hops) path in the network
- 2) Generate a lightpath with the shortest path and the first channel for demand d .

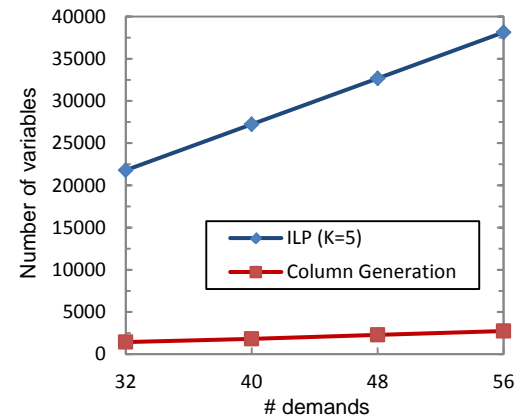
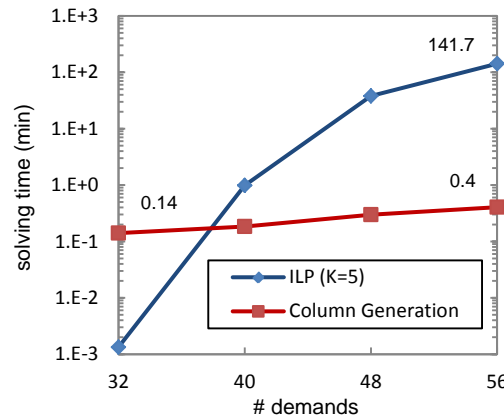
Pricing Problem

- 1) For each demand d and each channel in C_d , compute the shortest path in the network with link metrics:

$$f_e(c) = \sum_{s \in S(c)} \pi_{es} \quad c \in C_d$$

- 2) Return those lightpaths (route + channel) with the highest positive reduced costs (if any)

Exhaustive search of channels optimized by means of Floyd-Warshall algorithm



* M. Ruiz, et al., "Column Generation Algorithm for RSA Problems in Flexgrid Optical Networks," Springer Photonic Network Communications, 2013.

The Dijkstra's Shortest Path algorithm

```
Procedure Dijkstra (N, E, source)
begin
  S := {source}, T = N - {source}
  d(source) = 0 and pred(source) = 0
  d(j) = ∞ for each j ≠ source
  update(source)
  while S ≠ N do
    let i ∈ T be a node for which
      d(i) = min {d(j) : j ∈ T}
    S = S ∪ {i}, T = T - {i}
    update(i)
end
```

```
Procedure Update (i)
  for each (i, j) ∈ E(i) do
    if d(j) > d(i) + cij then
      d(j) = d(i) + cij
      pred(j) = i
```

- Each node i is labeled with the aggregated metric $d(i)$ from the source node and with its predecessor $pred(i)$.
- the route $source-i$ (subset of links $E(source, i) \subseteq E$) can be computed visiting the predecessor node starting from i , until source node is reached.

Dijkstra-based RSA (1/2)

```

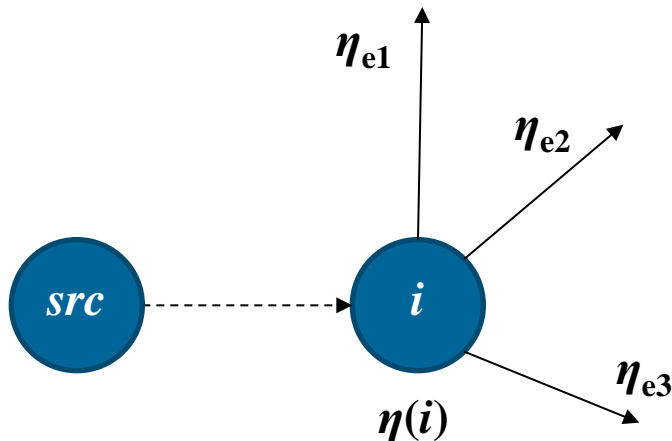
Procedure Update ( $i$ )
  for each  $(i, j) \in E(i)$  do
    if  $\pi(i, j) = 1$  and  $d(j) > d(i) + c_{ij}$ 
    then
       $d(j) = d(i) + c_{ij}$ 
       $\text{pred}(j) = i$ 
    
```

- The label also contains $\eta_s(i)$, the aggregated state of frequency slice s

$$\eta_s(i) = \prod_{e \in E(\text{source}, i)} \eta_{es} \quad \forall s \in S$$

- The downstream node j of node i updates the label only if at least one channel is available, computing:

$$\pi(e = (i, j)) = \begin{cases} 1 & \exists c \in C(d) : \eta_s(i) \cdot \eta_{es} = 1 \quad \forall s \in S(c) \\ 0 & \text{otherwise} \end{cases}$$



Dijkstra-based RSA (2/2)

- Spectrum allocation can be done implementing any heuristic, such:
 - First Fit
 - Random
 - Least fragmented spectrum
 - etc.
- Modulation formats, reachability, etc, can be easily included.



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Part III

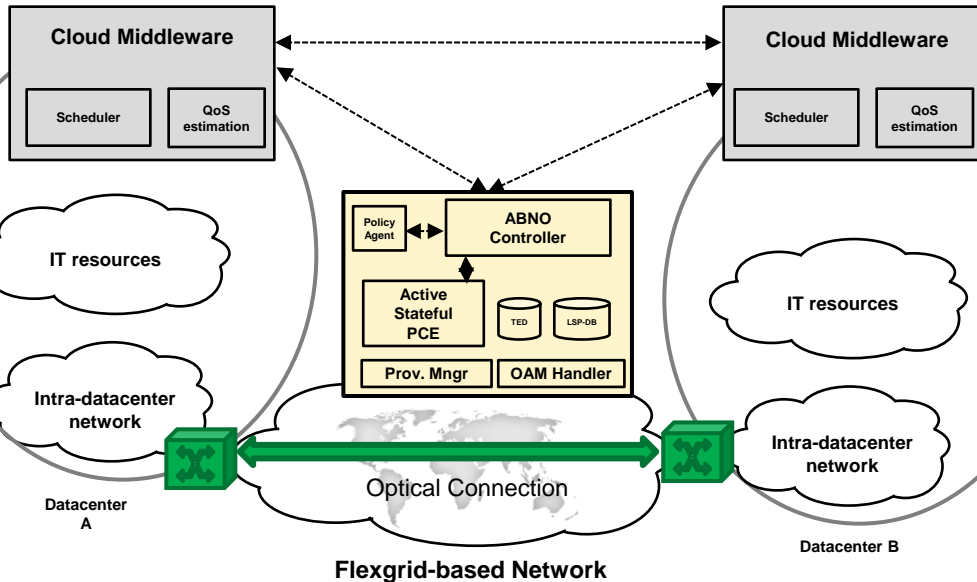
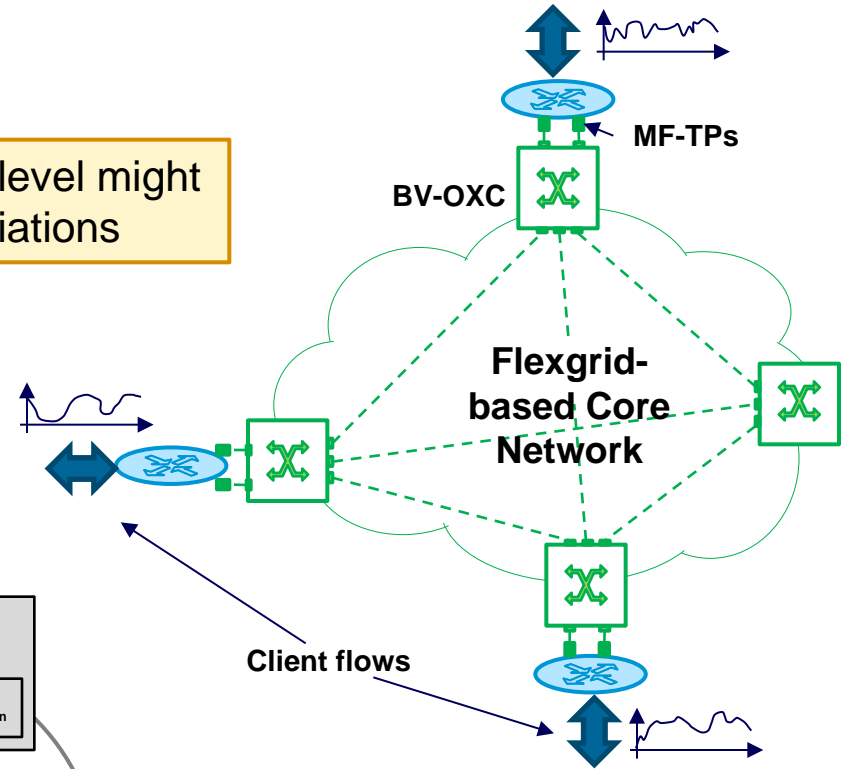
Advanced RSA

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Source of traffic variations

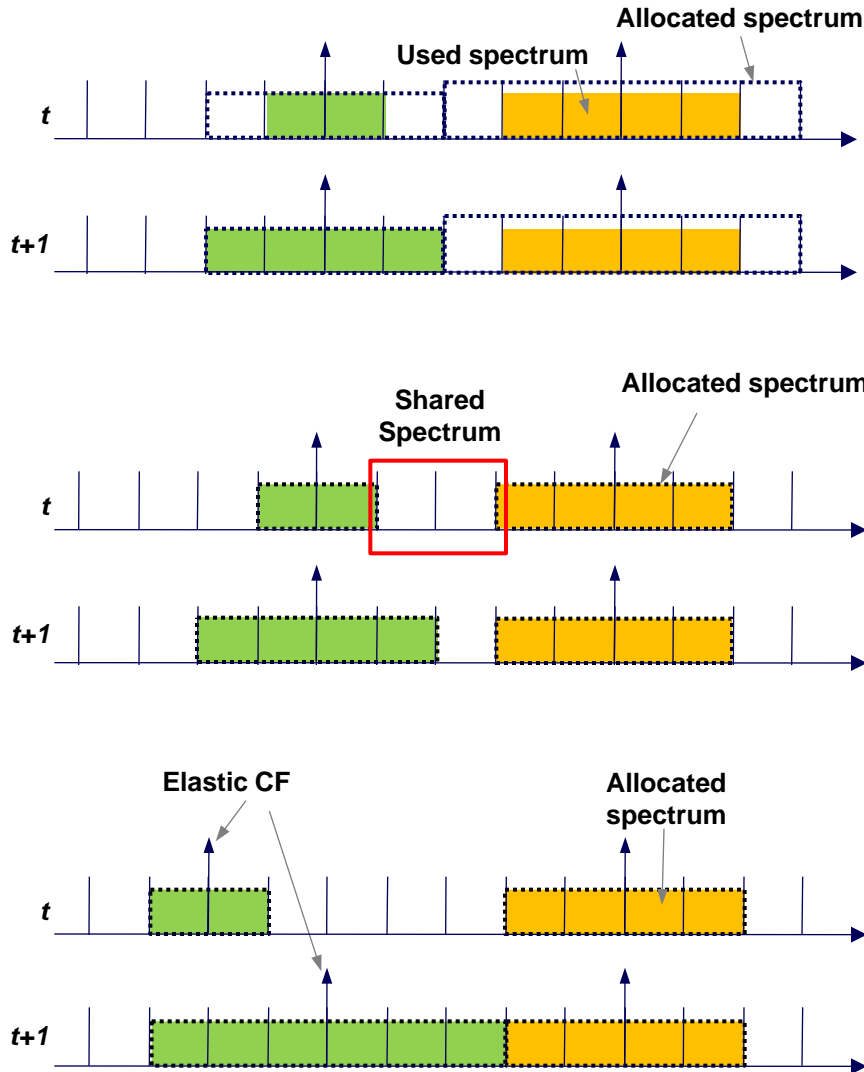
Reducing aggregation level might increase traffic variations

Datacenter interconnection to transfer bulk data



* L. Velasco, et al., "Cross-Stratum Orchestration and Flexgrid Optical Networks for Datacenter Federations," accepted in IEEE Network Magazine, 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

Multi-period RSA

- Find, for each demand in D :
 - a route and
 - a **SA for each time period in T** , constraining SA changes to a certain policy.
- Complexity depends on SA policy
 - SA between consecutive time periods is constrained by the chosen policy

RSA

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

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

MP-RSA

$$\sum_{p \in P(d)} x_p + x_d = 1 \quad \forall d \in D$$

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

Dynamic lightpath adaptation

- Given:
 - a core network topology represented by a graph $G(N, E)$;
 - a set S of available slices of a given spectral width for every link in E ;
 - a set L of lightpaths already established on the network; each lightpath l is defined by the tuple $\{R_l, f_l, s_l\}$, where the ordered set $R_l \subseteq E$ represents its physical route, f_l its central frequency and s_l the amount of frequency slices.
 - a lightpath $p \in L$ for which spectrum adaptation request arrives and the required number of frequency slices, $(s_p)^{req}$.
- Output:
 - the new values for the spectrum allocation of the given lightpath p : $\{R_p, f_p, (s_p)'\}$ and $\{R_p, (f_p)', (s_p)'\}$, respectively, if the *Semi-Elastic* and *Elastic* policy is used.
- Objective: maximize the amount of bit-rate served.

On-line Algorithms for Elastic SA

INPUT: $G(N,E), S, L, p, (s_p)^{req}$

OUTPUT: $(s_p)'$

- 1: **if** $(s_p)^{req} \leq s_p$ **then** $(s_p)' \leftarrow (s_p)^{req}$
- 2: **else**
- 3: $L^+ \leftarrow \emptyset, L^- \leftarrow \emptyset$
- 4: **for each** $e \in R_p$ **do**
- 5: $L^- \leftarrow L^- \cup \{l \in L: e \in R_l, \text{adjacents}(l, p), f_l < f_p\}$
- 6: $L^+ \leftarrow L^+ \cup \{l \in L: e \in R_l, \text{adjacents}(l, p), f_l > f_p\}$
- 7: $s_{max} \leftarrow 2 * \min \{ \min \{ f_p - f_l - s_l, l \in L^- \}, \min \{ f_l - f_p - s_l, l \in L^+ \} \}$
- 8: $(s_p)' \leftarrow \min \{ s_{max}, (s_p)^{req} \}$
- 9: **return** $(s_p)'$

**Algorithm for the
semi-elastic policy**

**Algorithm for the
elastic policy**

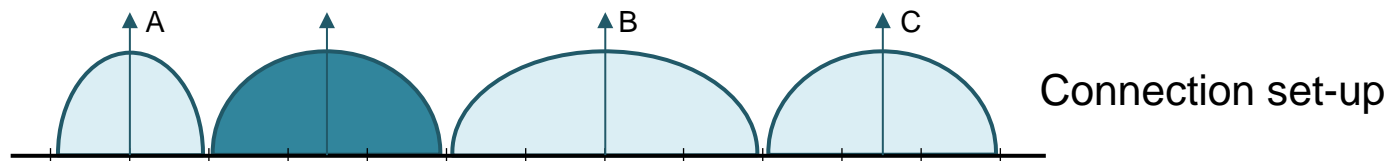
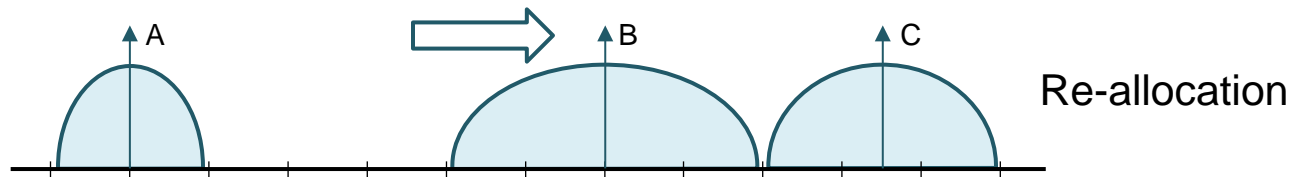
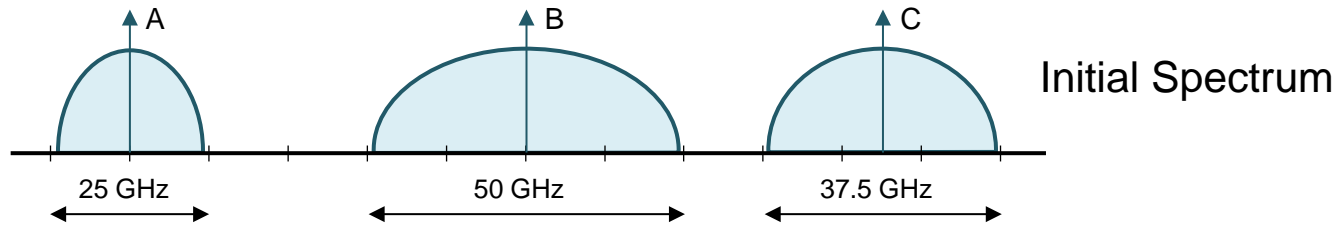
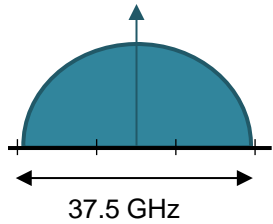
INPUT: $G(N,E), S, L, p, (s_p)^{req}$

OUTPUT: $(f_p)', (s_p)'$

- 1: **if** $(s_p)^{req} \leq s_p$ **then** $(s_p)' \leftarrow (s_p)^{req}; (f_p)' \leftarrow f_p$
- 2: **else**
- 3: $L^+ \leftarrow \emptyset, L^- \leftarrow \emptyset$
- 4: **for each** $e \in R_p$ **do**
- 5: $L^- \leftarrow L^- \cup \{l \in L: e \in R_l, \text{adjacents}(l, p), f_l < f_p\}$
- 6: $L^+ \leftarrow L^+ \cup \{l \in L: e \in R_l, \text{adjacents}(l, p), f_l > f_p\}$
- 7: $s_{max} \leftarrow \min \{ f_p - f_l - s_l, l \in L^- \} + \min \{ f_l - f_p - s_l, l \in L^+ \}$
- 8: $(s_p)' \leftarrow \min \{ s_{max}, (s_p)^{req} \}$
- 9: $(f_p)' \leftarrow \text{findSA_MinCFShifting}(p, (s_p)', L^+, L^-)$
- 10: **return** $\{(f_p)', (s_p)'\}$

* A. Asensio, et al., "Impact of Aggregation Level on the Performance of Dynamic Lightpath Adaptation under Time-Varying Traffic," in Proc. IEEE International Conference on Optical Network Design and Modeling (ONDM), 2013.

Example of Re-optimisation (Defragmentation)



Spectrum Reallocation (SPRESSO)

Parameters

Pm subset of P with the candidate paths, including $newP$. $Pm = P(newP) \cup \{newP\}$.

Variables

x_{pc} binary, 1 if channel c is assigned to path p , 0 otherwise.

y_p binary, 1 if path p is reallocated, 0 otherwise.

r integer with the number of already established paths to reallocate.

(SPRESSO) minimize r

subject to:

$$r = \sum_{p \in Pm \setminus \{newP\}} y_p$$

$$\sum_{c \in C(p)} x_{pc} = 1 \quad \forall p \in Pm$$

$$x_{pc} - \omega_{pc} \leq y_p \quad \forall p \in Pm, c \in C(p)$$

$$\sum_{p \in P(e)} \sum_{c \in C(p)} \delta_{cs} \cdot x_{pc} \leq \eta_{es} \quad \forall e \in E, s \in S$$

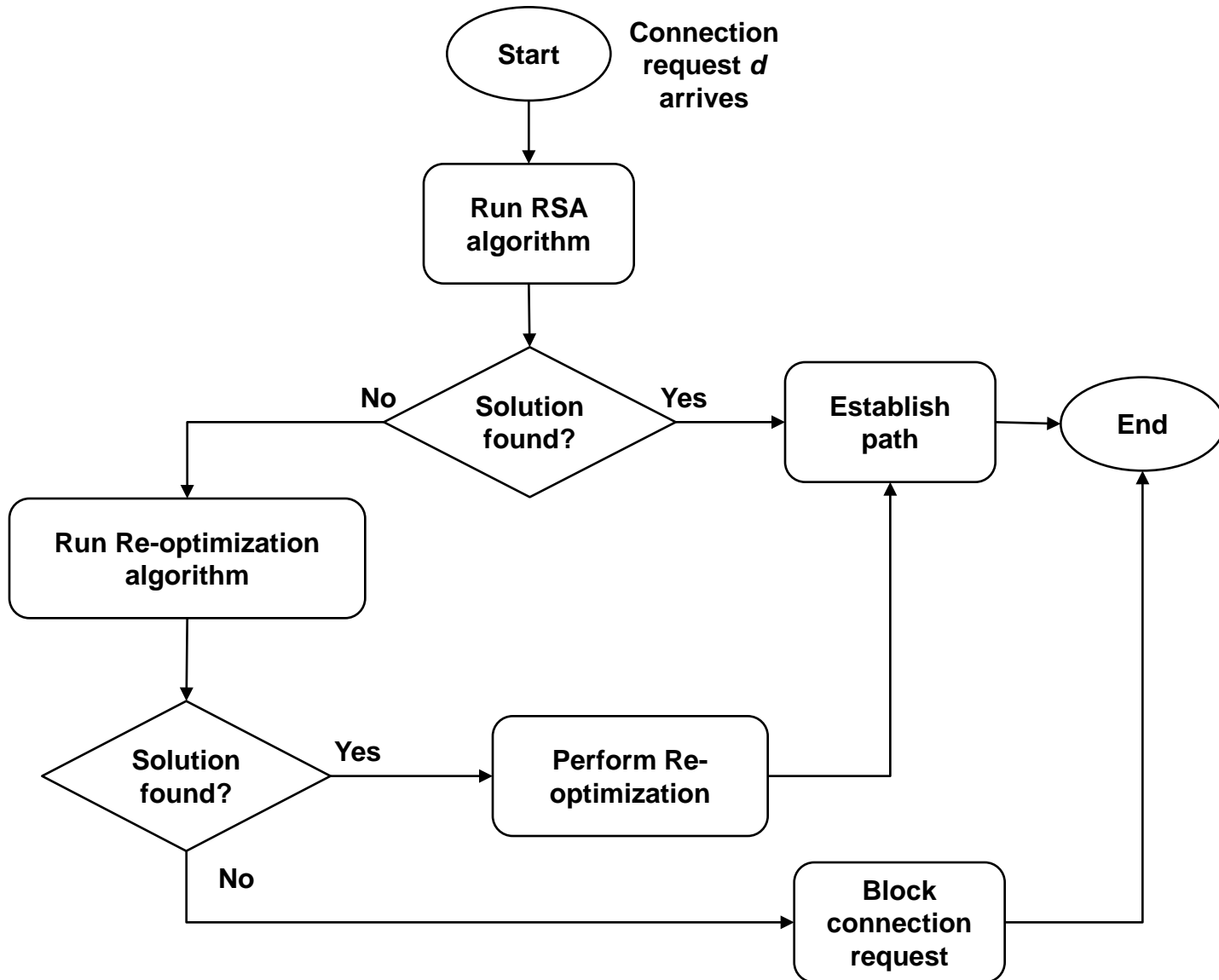
$$r \leq \max R$$

$O(|Pm| \cdot |C|)$ variables

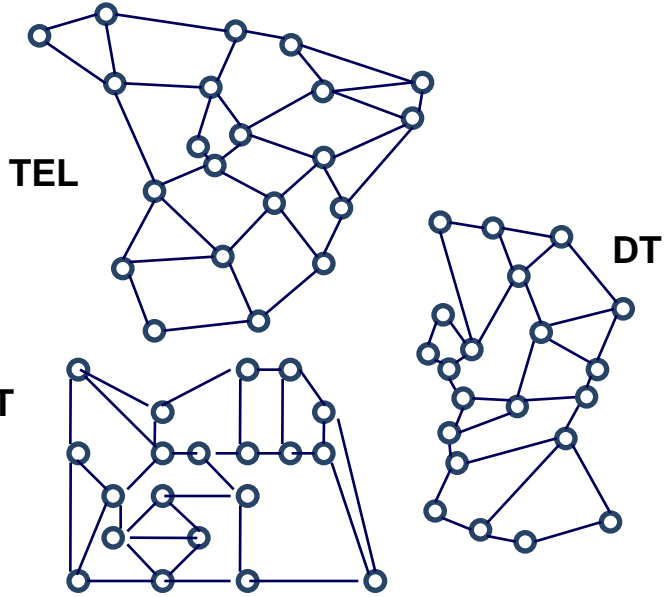
$O(|Pm| \cdot |C| + |E| \cdot |S|)$ constraints

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

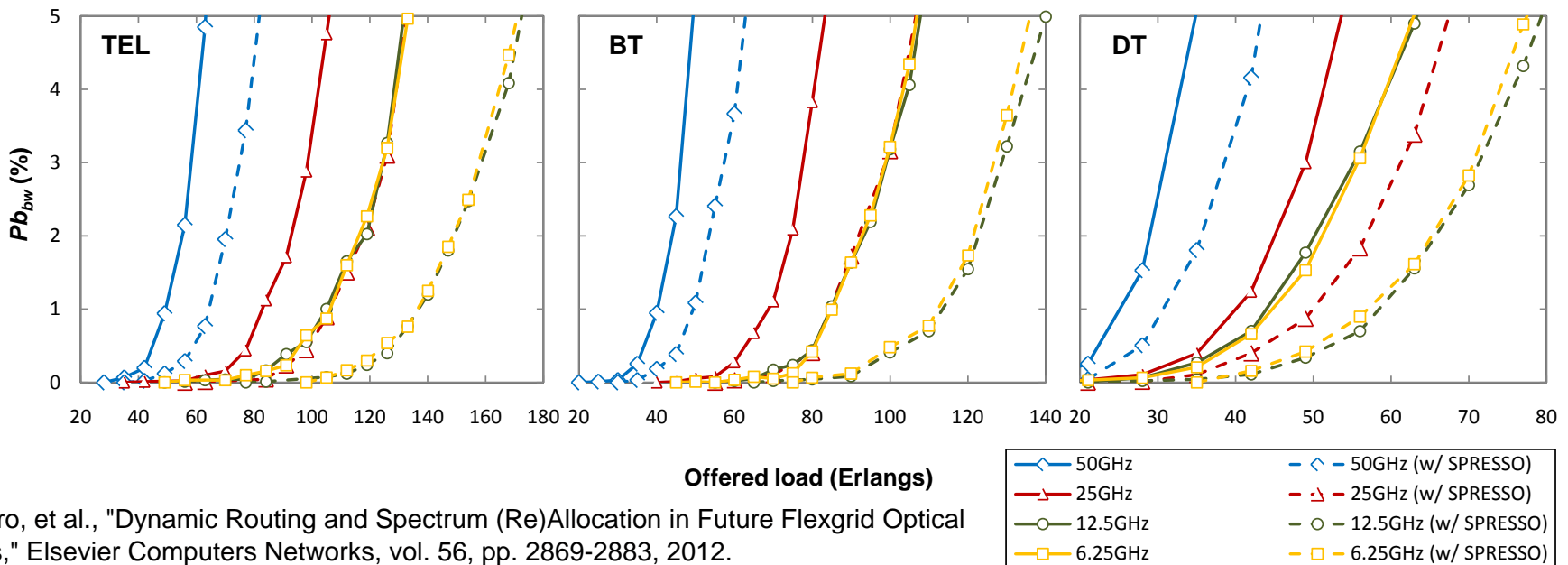
Provisioning-triggered re-optimization



Gains of Using SPRESSO



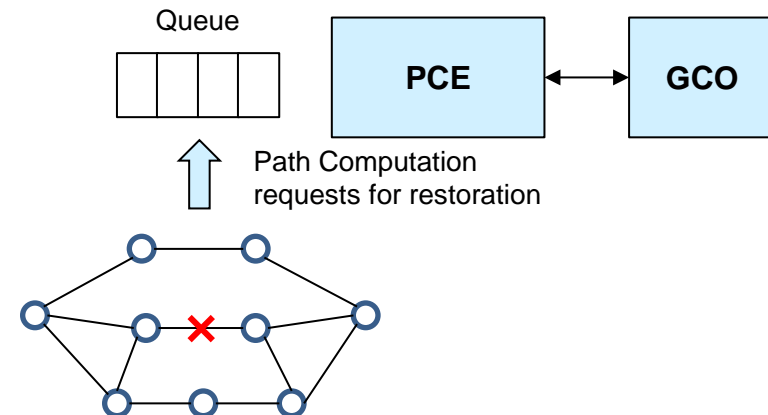
Network	25 GHz	12.5 GHz	6.25 GHz
TEL	30,4%	28,4%	30,3%
BT	22,9%	23,0%	34,1%
DT	22,2%	24,8%	33,0%



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

Bulk path computation

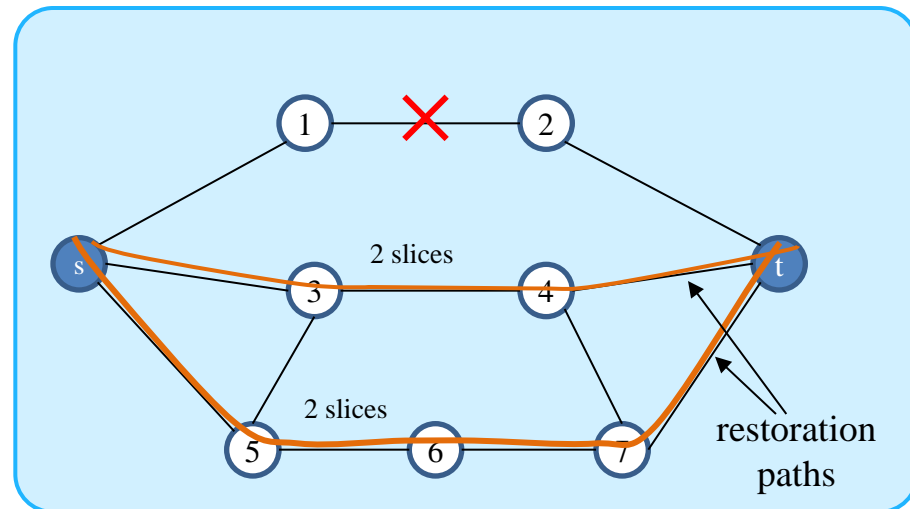
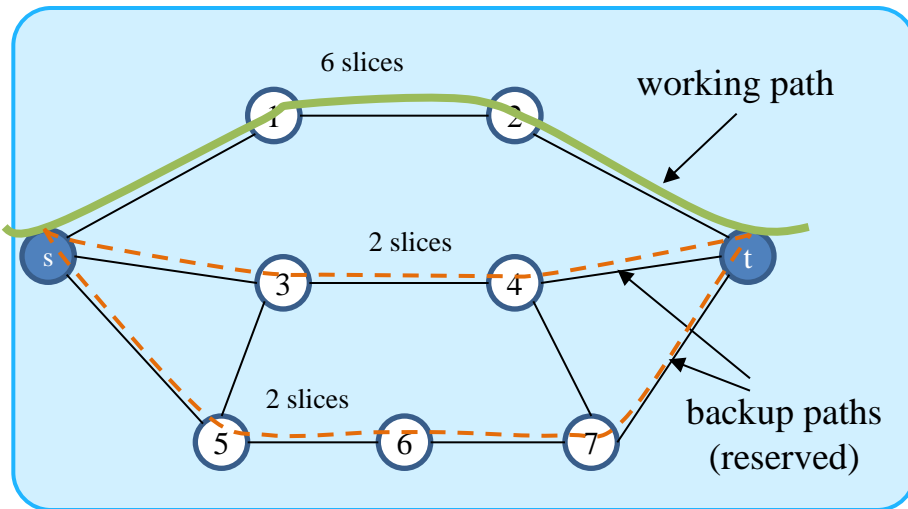
- Path computation for a set of connection requests.
 - the bulk of path requests is computed attaining the optimal solution for the whole set.
 - Increases optimality but increases also provisioning time.
- Bulk path computation can be used for restoration.
 - Reduces resource contention.
 - Increases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



* R. Martínez, et al., "Experimental Validation of Dynamic Restoration in GMPLS-controlled Multi-layer Networks using PCE-based Global Concurrent Optimization," in Proc. IEEE/OSA Optical Fiber Communication Conference (OFC), 2013.

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., "Single-path Provisioning with Multi-path Recovery in Flexgrid Optical Networks," International Workshop on Reliable Networks Design and Modeling (RNDM), 2012



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Part IV

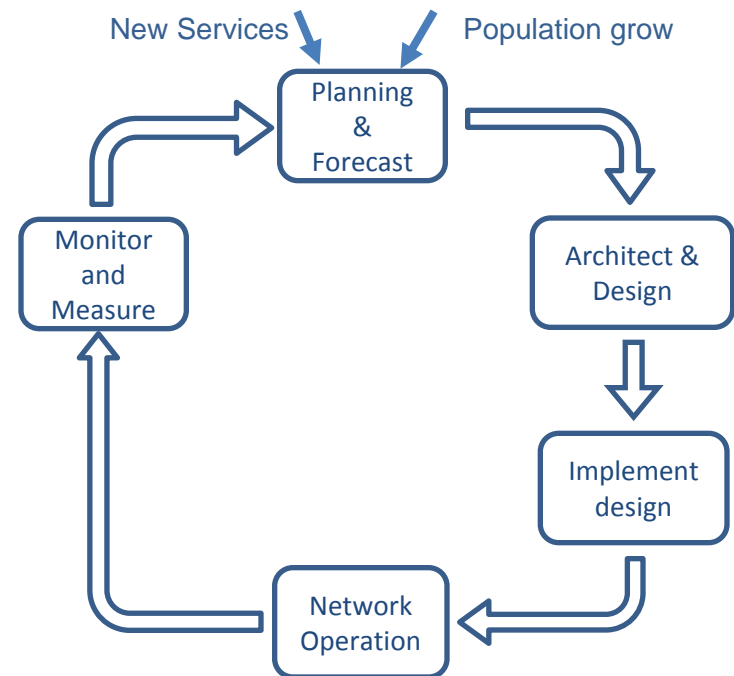
Off-line Network Planning

Luis Velasco

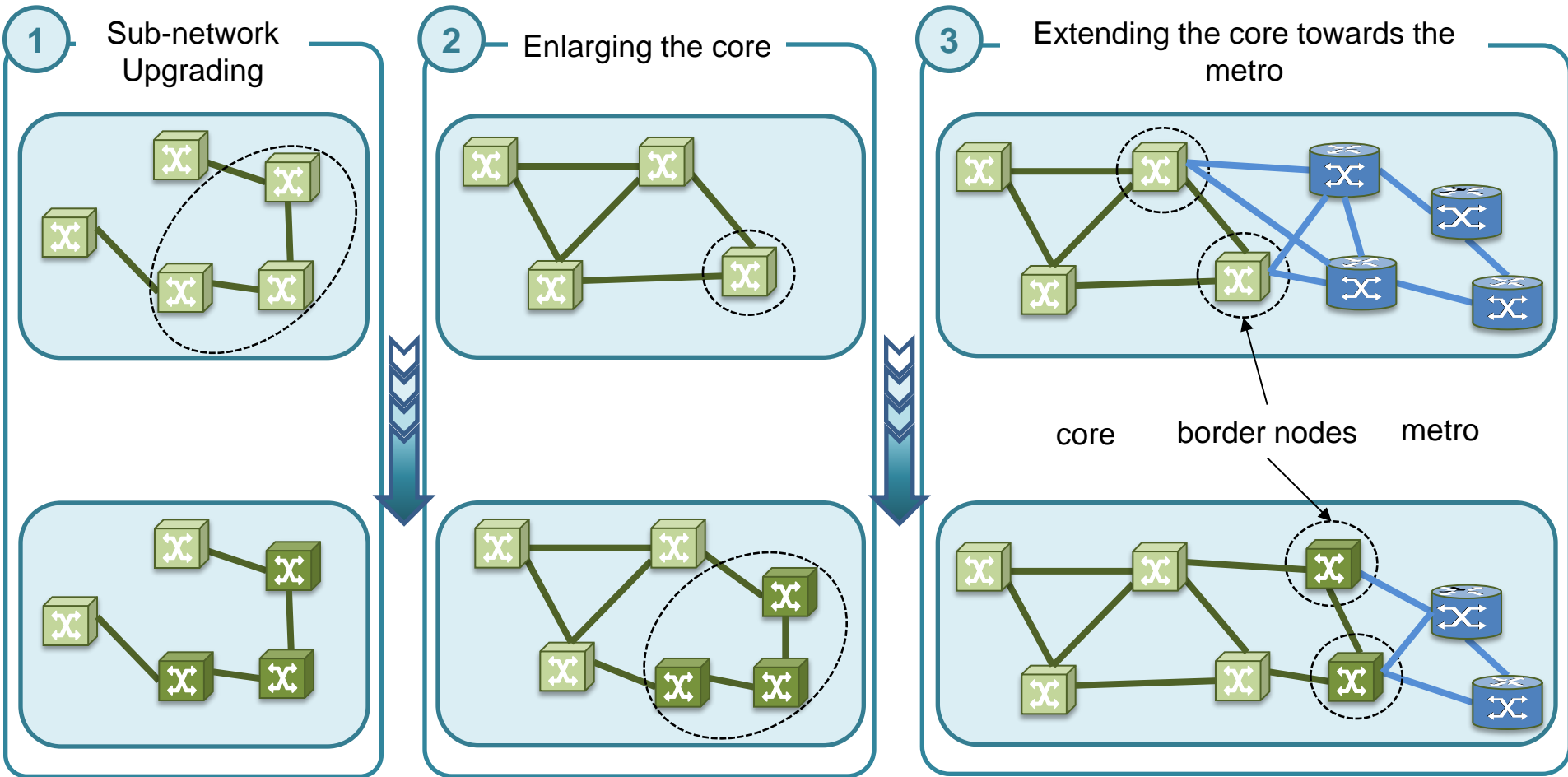
Network Life Cycle

- 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.



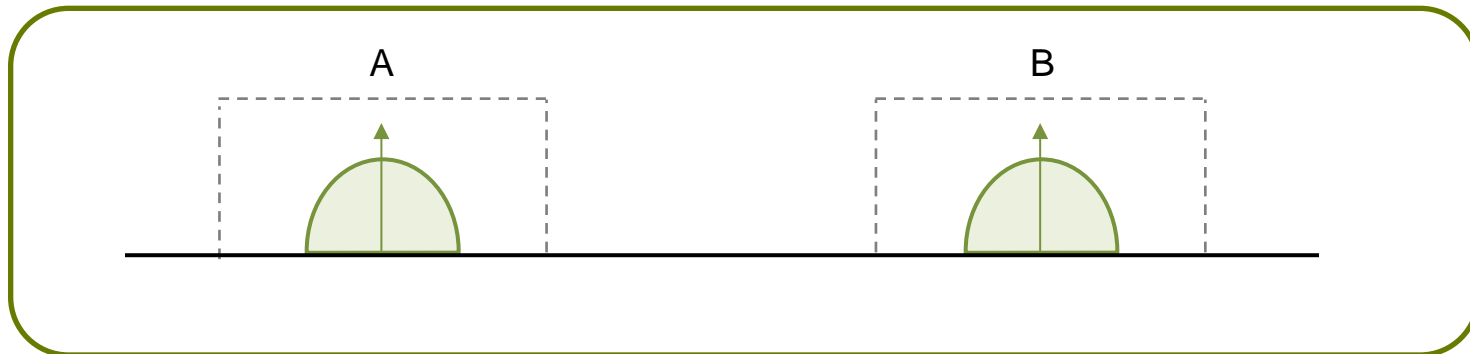
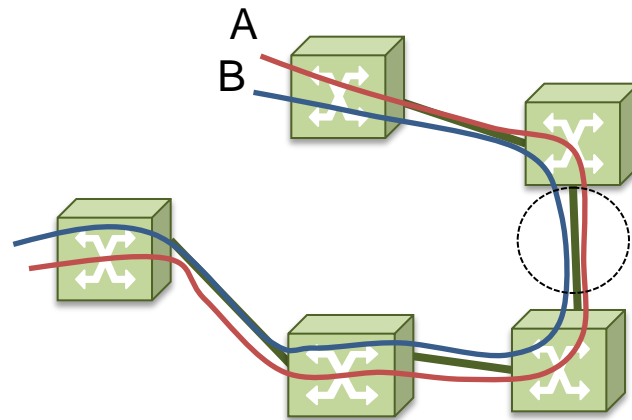
Migrating Towards Flexgrid Technology



* M. Ruiz, et al, "Planning Fixed to Flexgrid Gradual Migration: Drivers and Open Issues," submitted to IEEE Communications Magazine, 2014.

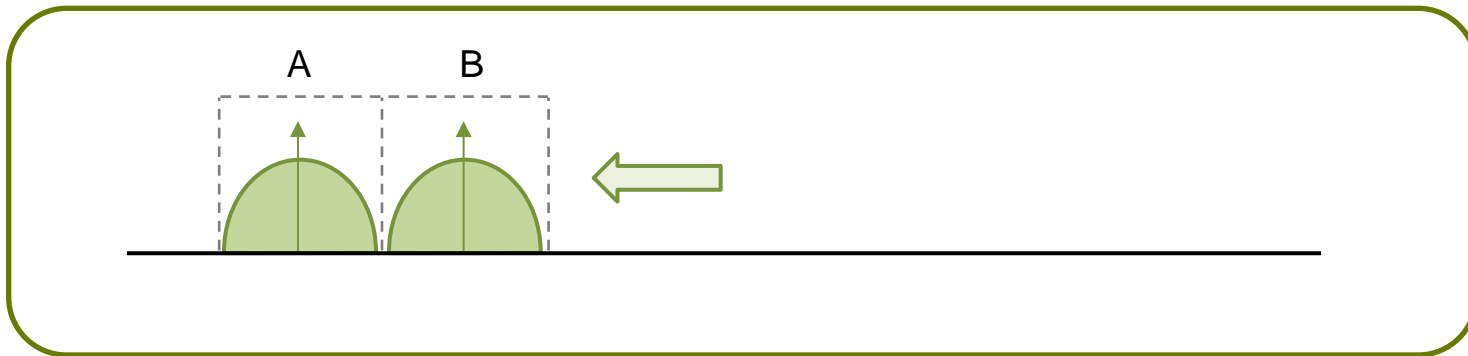
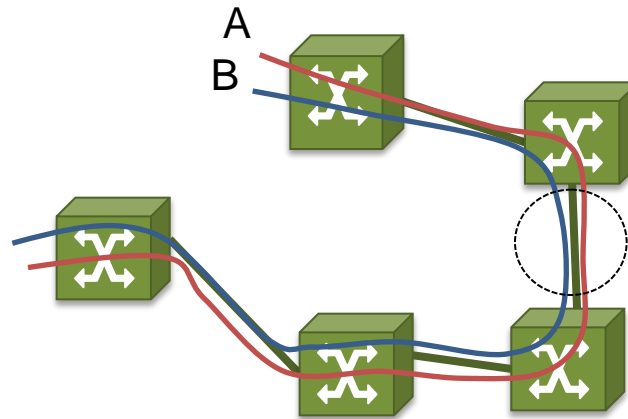
Migrating connections (1/4)

Fixed grid



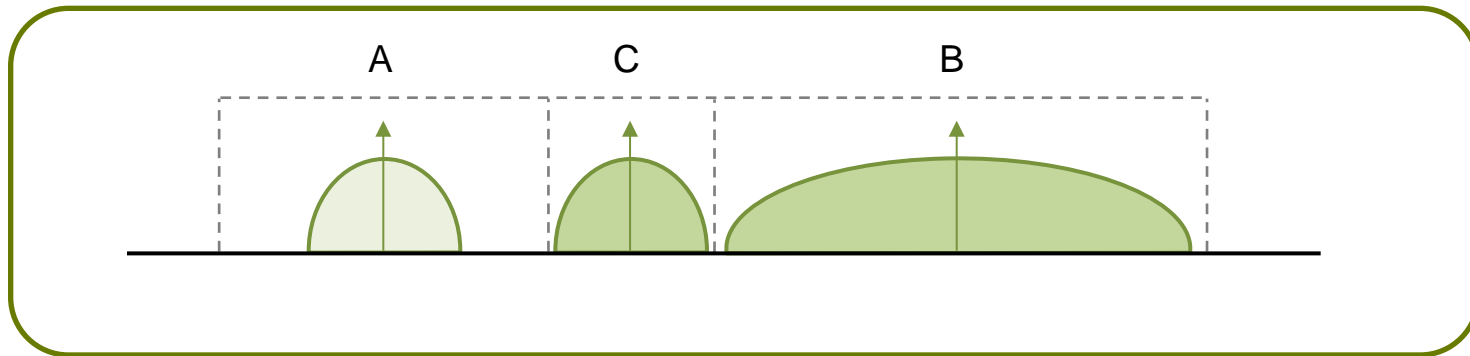
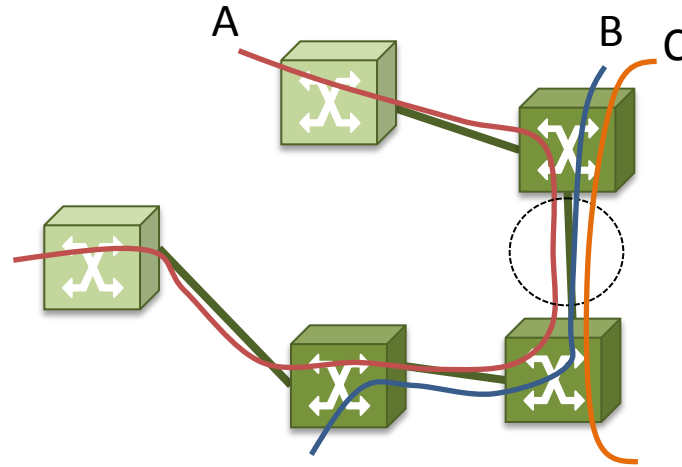
Migrating connections (2/4)

Flexgrid



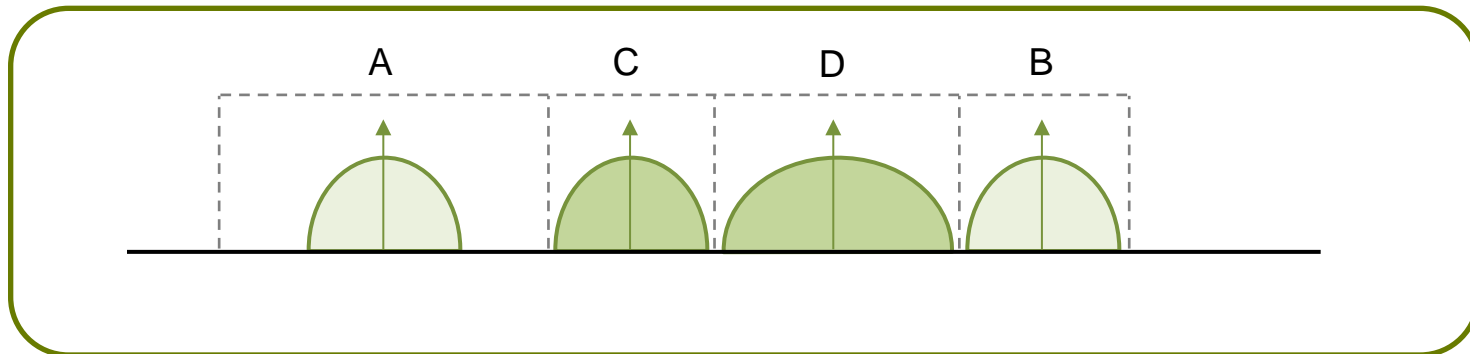
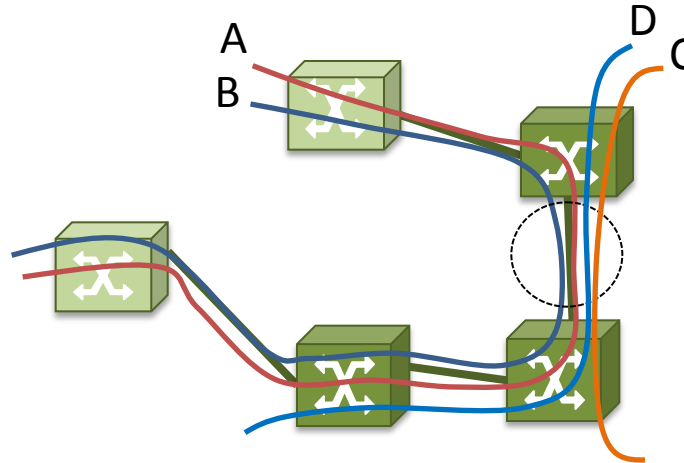
Migrating connections (3/4)

Mixed grid

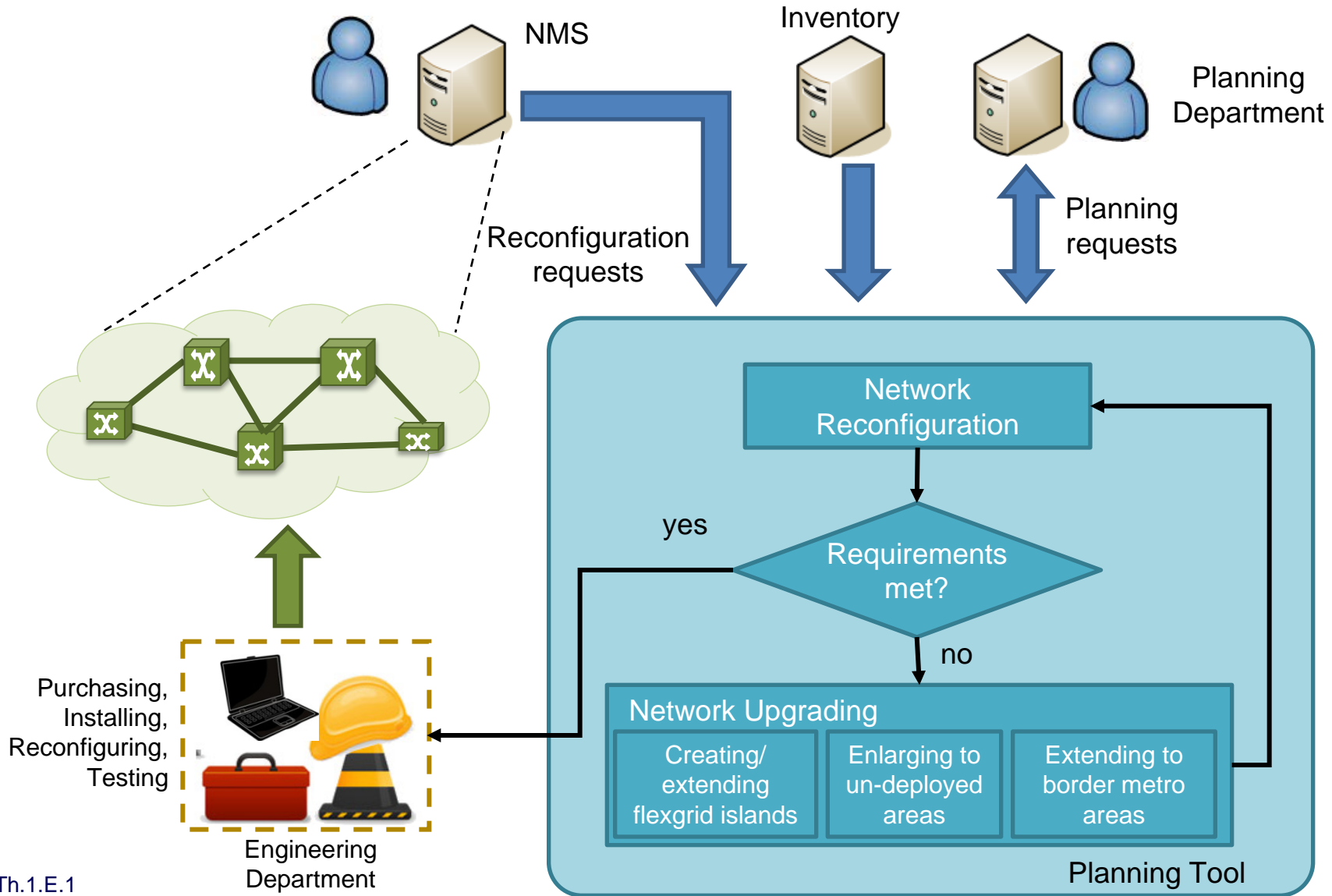


Migrating connections (4/4)

Mixed grid



Migration flow chart





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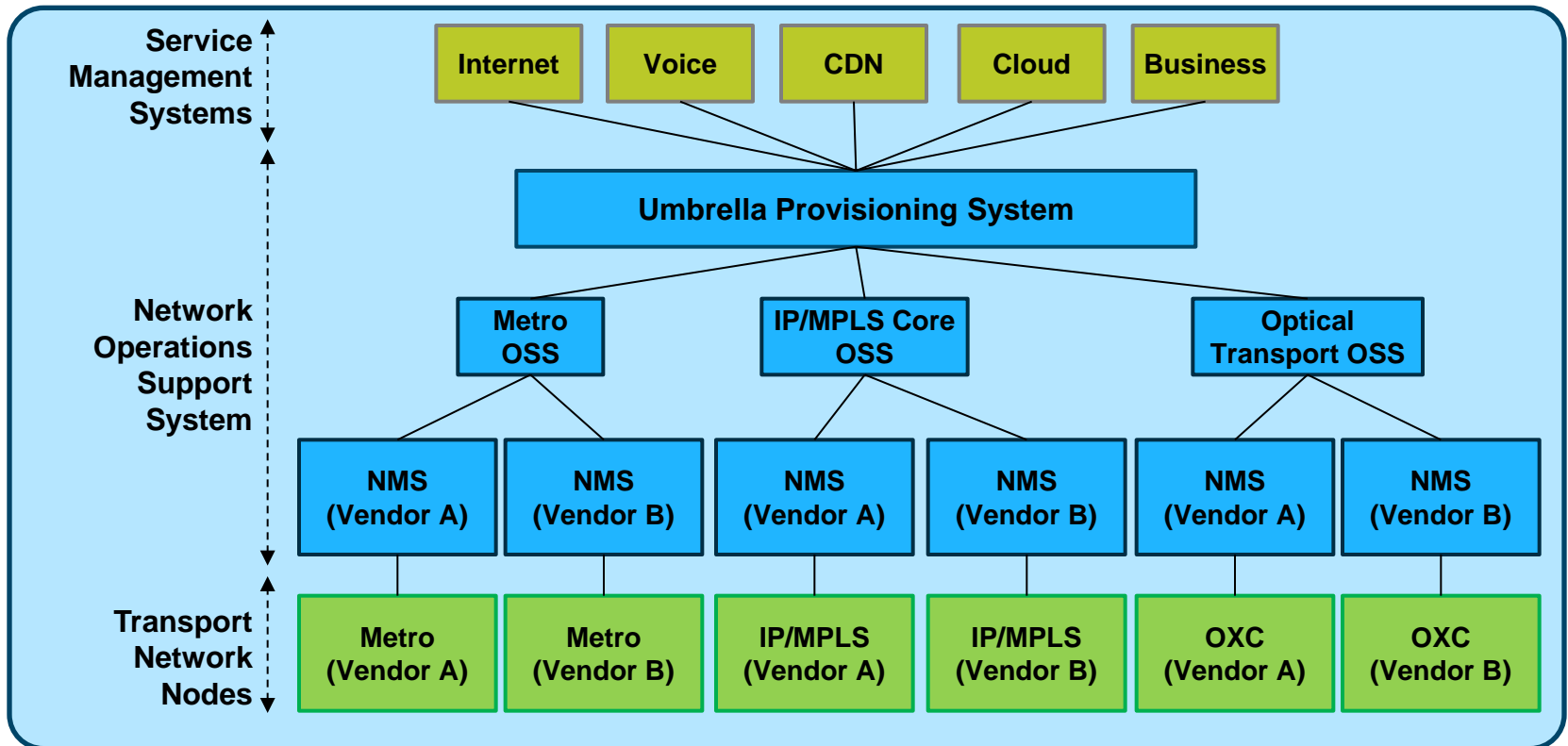


Part V

In-operation Network Planning

Luis Velasco

Static Network Operation



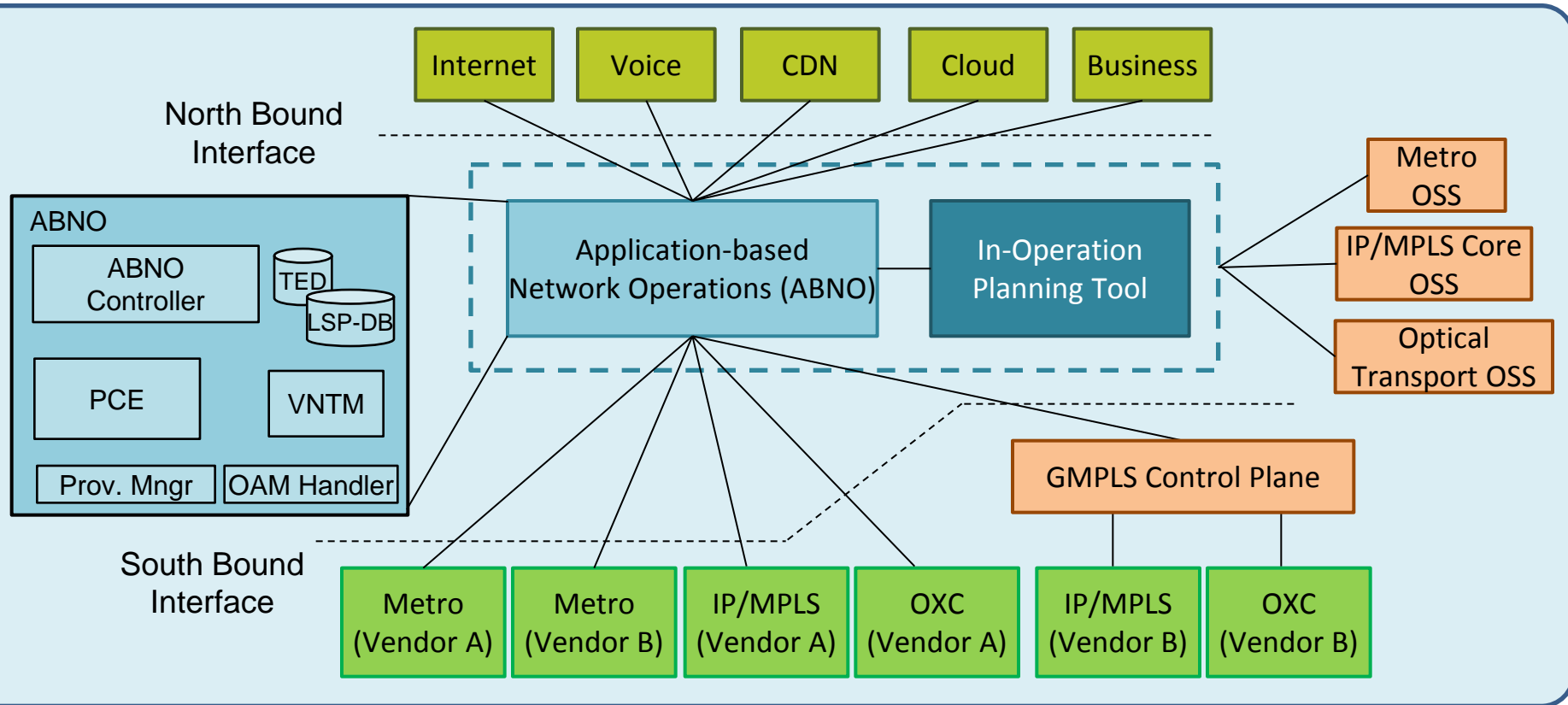
IETF architectures supporting in-operation Planning (1/2)

Architecture	Strengths	Weaknesses
Stateless PCE	<ul style="list-style-type: none"> • Path computation can be off-loaded onto a dedicated entity capable of complex computations with tailored algorithms and functions. • Has a standard and mature interface and protocol. • Supports simple optimisation, such as bulk path computation. 	<ul style="list-style-type: none"> • Is unaware of existing LSPs and has no view of the current network resource utilisation and key choke points. • Cannot configure by itself any LSP in the network. • Delays need to be introduced to sequence LSP set-up.
Stateful PCE	<ul style="list-style-type: none"> • Maintains a database of LSPs that are active in the network, i.e. so that new requests can be more efficiently placed optimising network resources. • Supports optimization involving already established LSPs. 	<ul style="list-style-type: none"> • More complex than a stateless PCE, requires additional database and synchronization. • No existing LSPs can be modified, e.g. for network re-configuration purposes.

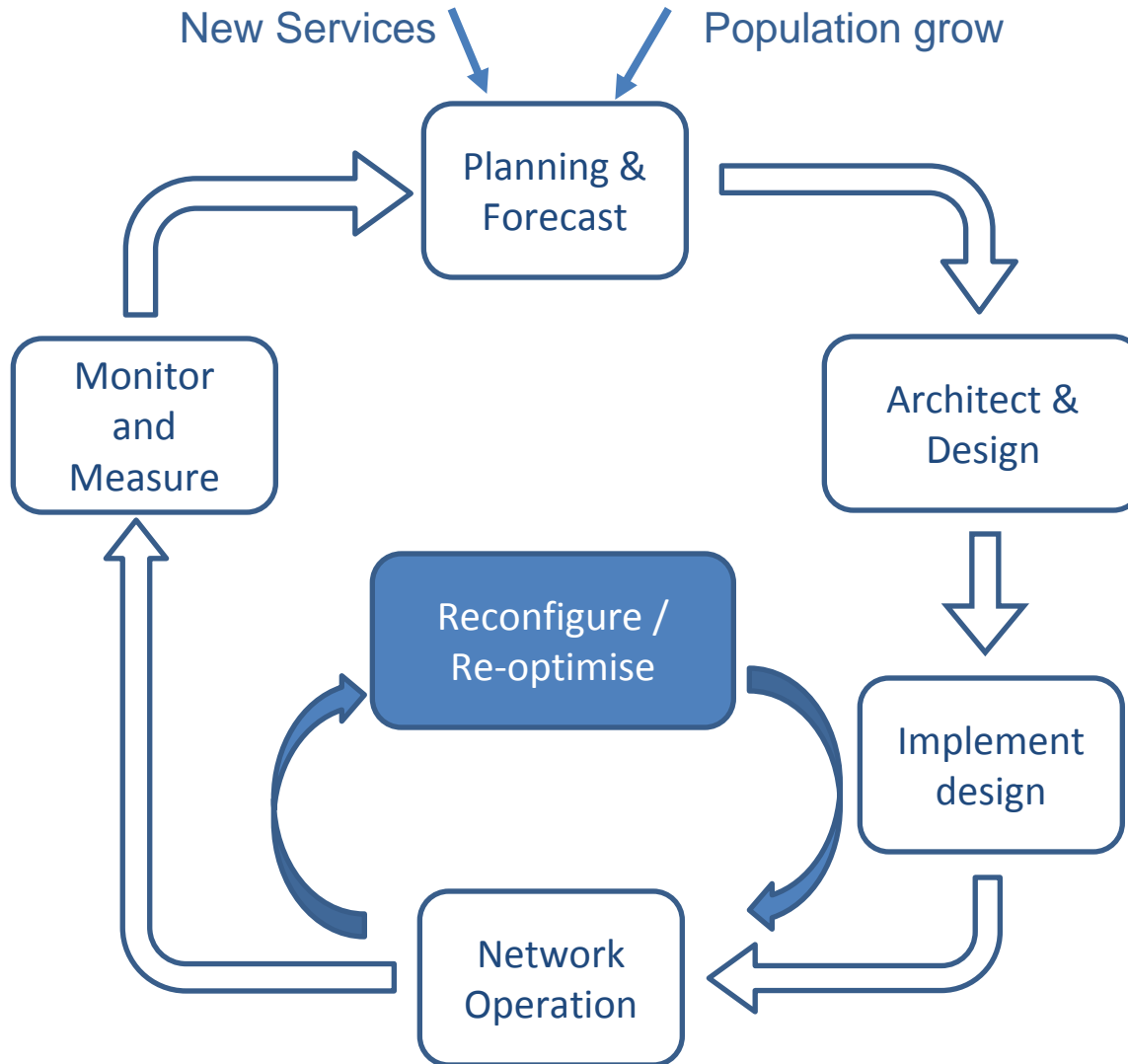
IETF architectures supporting in-operation Planning (2/2)

Architecture	Strengths	Weaknesses
<p>Active Stateful PCE</p>	<ul style="list-style-type: none"> • Capable of responding to changes in network resource availability and predicted demands and reroute existing LSPs for increased network resource efficiency. • Supports complex reconfiguration and re-optimization, even in multilayer networks. 	<ul style="list-style-type: none"> • No new LSPs can be created, e.g. for VNT re-optimisation purposes. • Requires protocol extensions to modify and/or instantiate (if the capability is available) LSPs.
<p>ABNO</p>	<ul style="list-style-type: none"> • Provides a network control system for coordinating OSS and NMS requests to compute paths, enforce policies, and manage network resources for the benefit of the applications that use the network. • New LSPs can be created for in-operation planning. VNTM in charge of VNT re-configuration. • Supports deployment of solutions in multi-technology scenarios (NetConf, OpenFlow, control plane, etc.) 	<ul style="list-style-type: none"> • Requires implementation of a number of key components in addition to the PCE function. • Some interfaces still need to be defined and standardized.

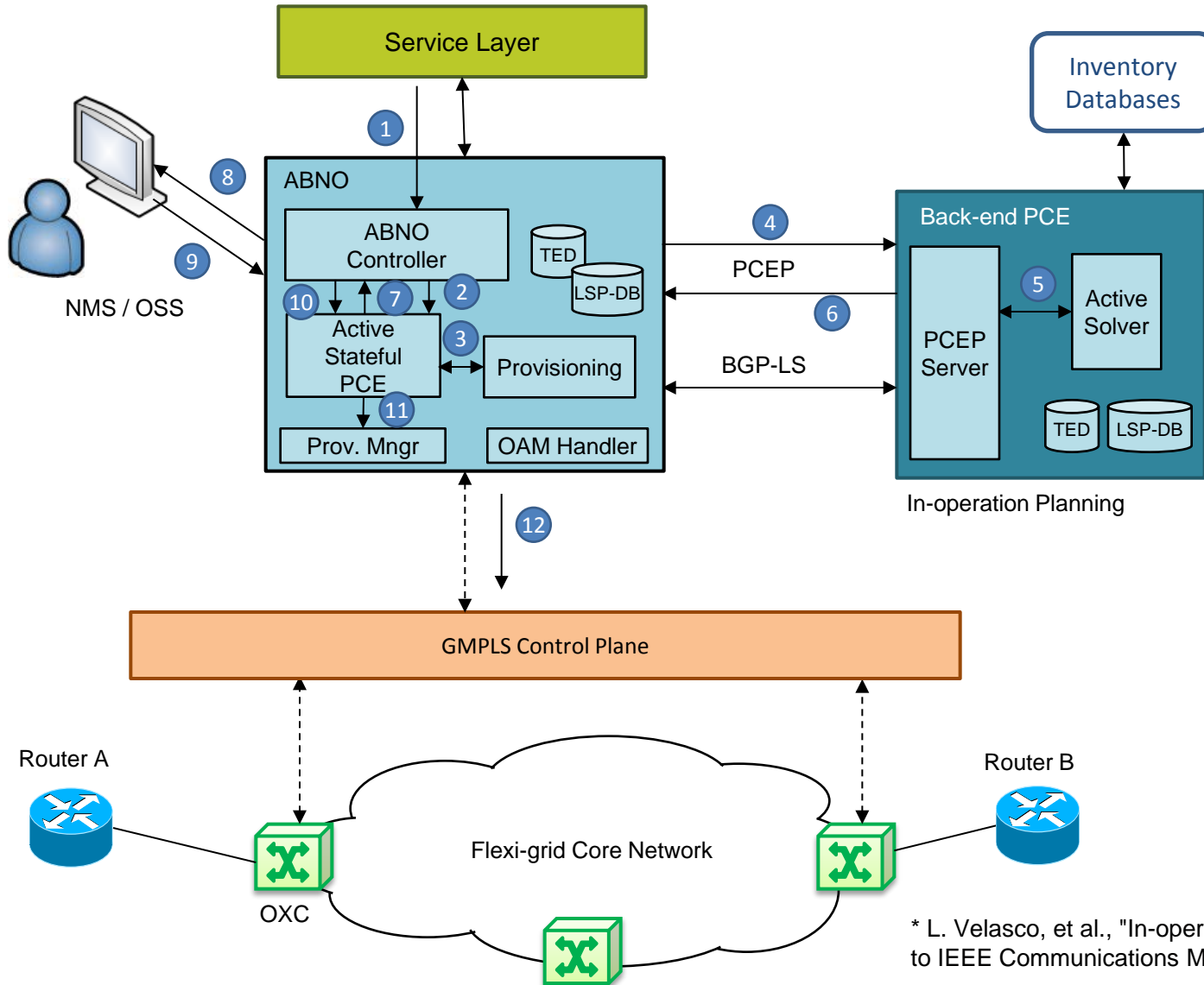
Migration towards in-operation network planning



Extended Networks Life Cycle

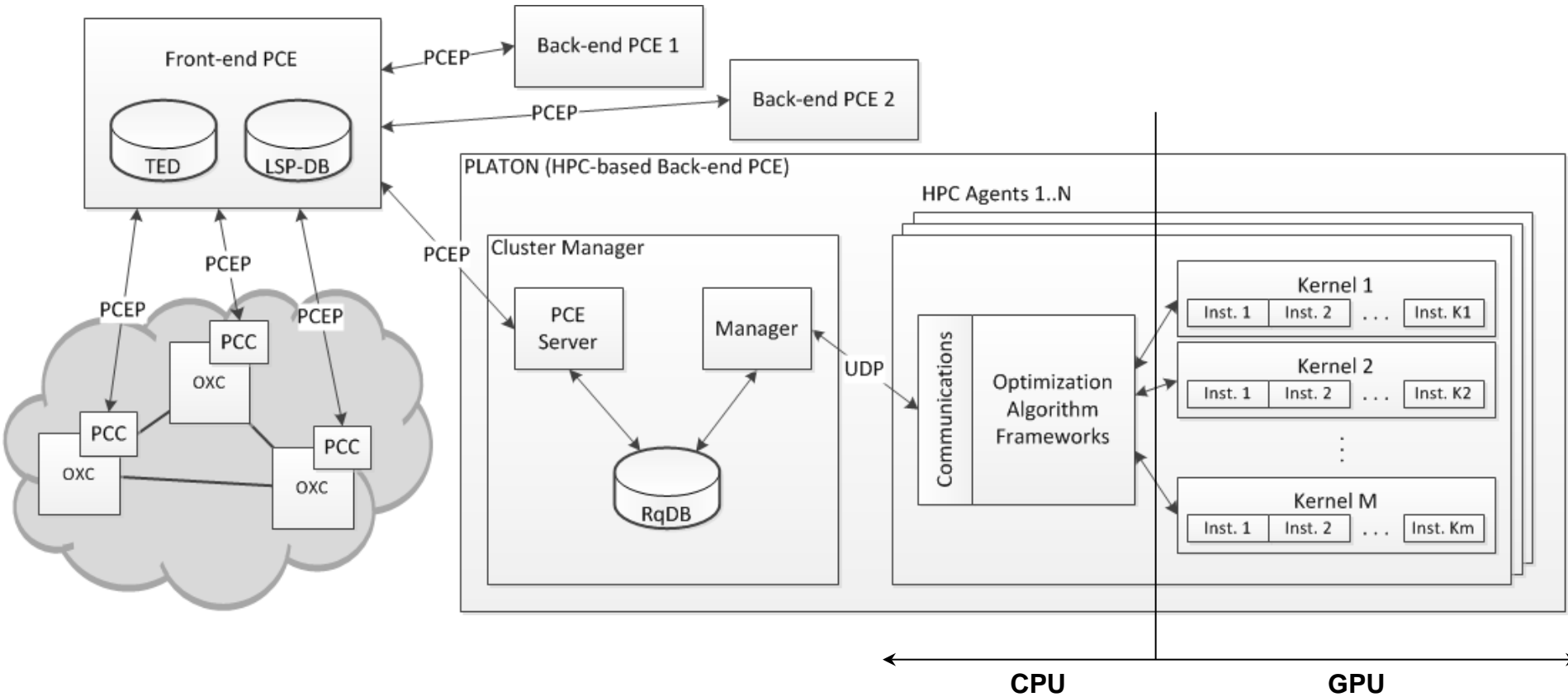


Re-optimisation Process



* L. Velasco, et al., "In-operation Network Planning," submitted to IEEE Communications Magazine, 2014.

In-Operation Planning Tool: PLATON



* L. Gifre, et al. "Architecture of a Specialized Back-end High Performance Computing-based PCE for Flexgrid Networks," in Proc. IEEE International Conference on Transparent Optical Networks (ICTON), 2013.

Conclusions

- **Basic RSA algorithms have been reviewed**
- **Elastic SA:** Semi-elastic and Elastic policies
- **Off-line planning:** and example for gradual migration process from fixed to Flexgrid has been presented.
- **Re-optimization** can be performed to increase network performance.
- A control and management architecture to support **in-operation planning**.
 - The architecture allows dynamic network operation and to reconfigure and re-optimize the network near real-time in response to changes.
 - Networks life cycle is extended achieving better resource utilization.
 - Process automation reduces manual interventions and, consequently, OPEX.
- **PLATON:** an In-Operation Planning Tool has been presented.



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Thank you for your attention!

Solving Routing and Spectrum Allocation Related Optimization Problems

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