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High Speed Communication Networks Laboratory
National Technical University of ATHENS

RS1: Elastic Optical Networks

Incremental Planning of Multi-layer Elastic Optical Networks

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Motivation

Conventional approach:

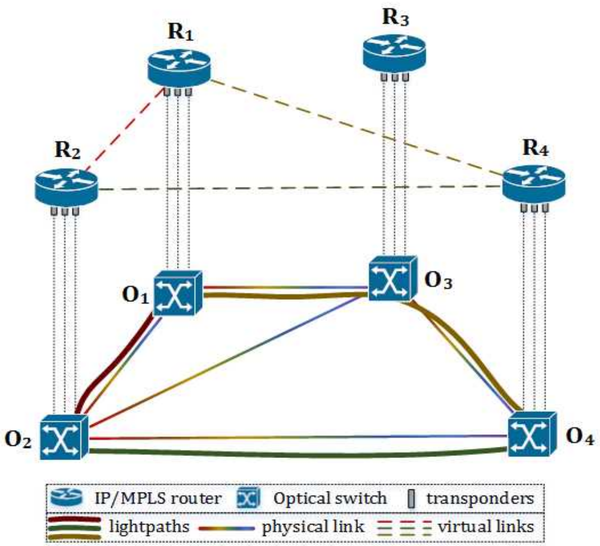
- ☒ optical transport networks have **long upgrade cycles**
- ☒ optical network and its edges are upgraded **independently**
- ☒ both result to overprovisioning, underutilized equipment and **unnecessary investments**

Long upgrade cycles and single layer planning were adopted in the past to account for the lack of **optical agility** and **dynamic control/management** of optical network resources

Emerging elastic optical technology and Software Defined Networking paradigm increase flexibility, enabling a **joint multi-layer operation** and **short network** re-optimization/upgrade **cycles**:

- ☑ operate the network close to its true capabilities and postpone or avoid investments
- ☑ multilayer coordination allows more efficient resources usage
- ☑ capture traffic dynamicity and technology maturation (depreciation & better technology)

Network Model



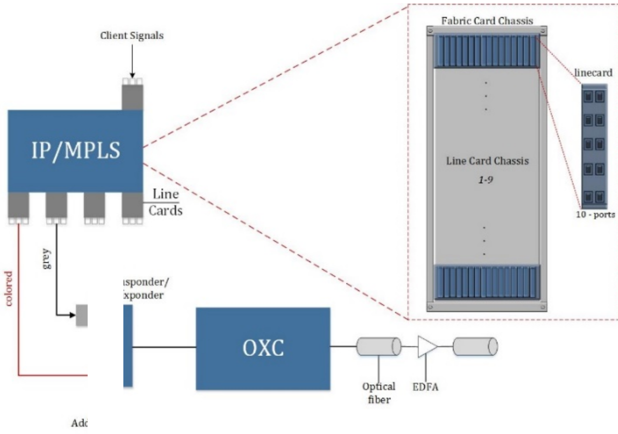
IP-over-Elastic Optical Network

Planning an IP over EON consists of 3 inter-related sub-problems:

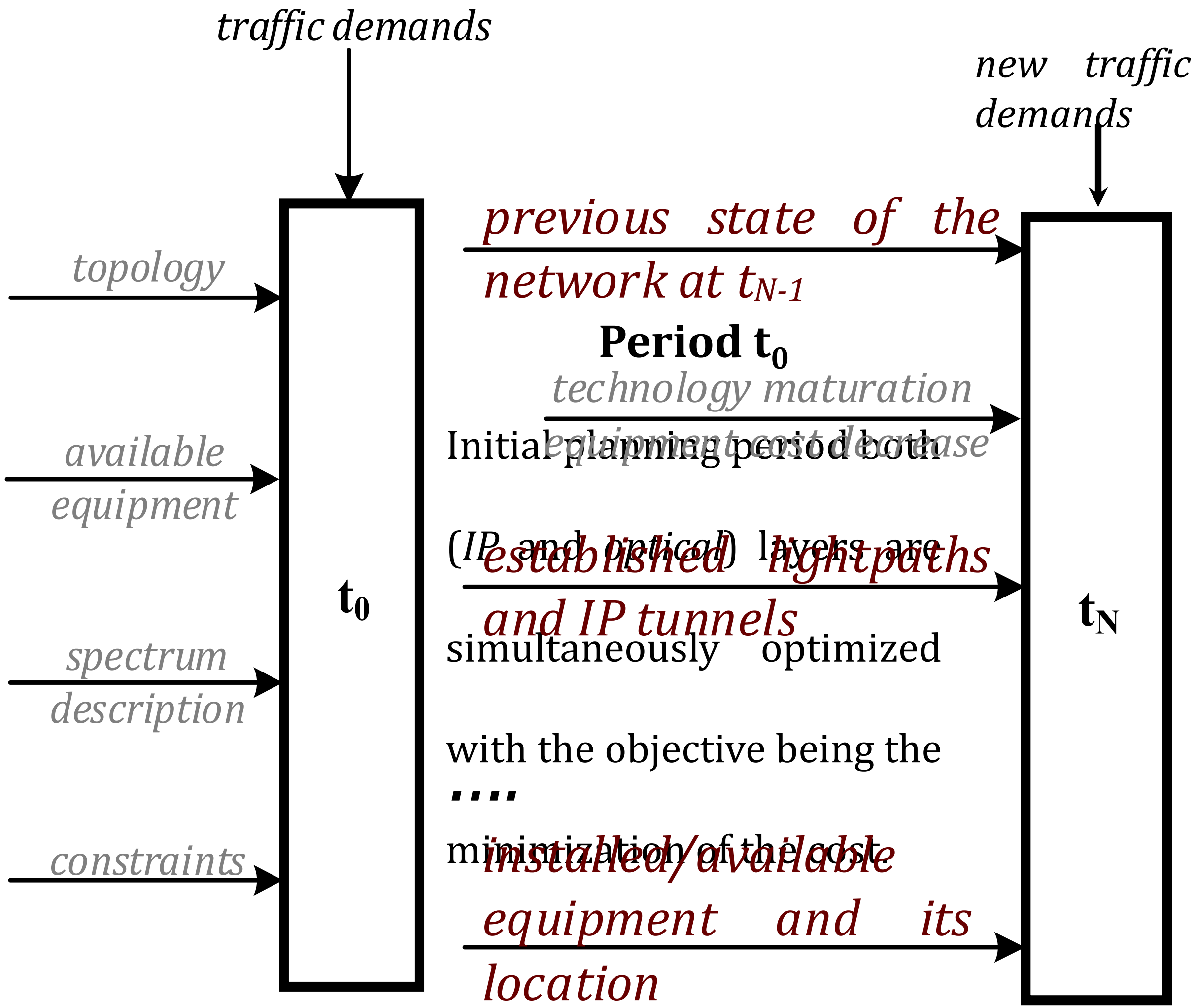
- Optical network: virtual topology design
  - Routing of lightpaths and Modulation Level selection (RML)
  - Spectrum Allocation (SA)
- IP routing (IPR) on top of the virtual topology

Multilayer CAPEX model

- Optical: flex-grid enabled ROADMs and tunable - Bandwidth Variable Transponders (BVTs)
- IP: Modular IP/MPLS routers organized into 3 component classes: basic node (3 types of chassis), line-cards, and short reach transceivers



Incremental Multi-layer Network Planning (1/2)



Period t_N:

Input

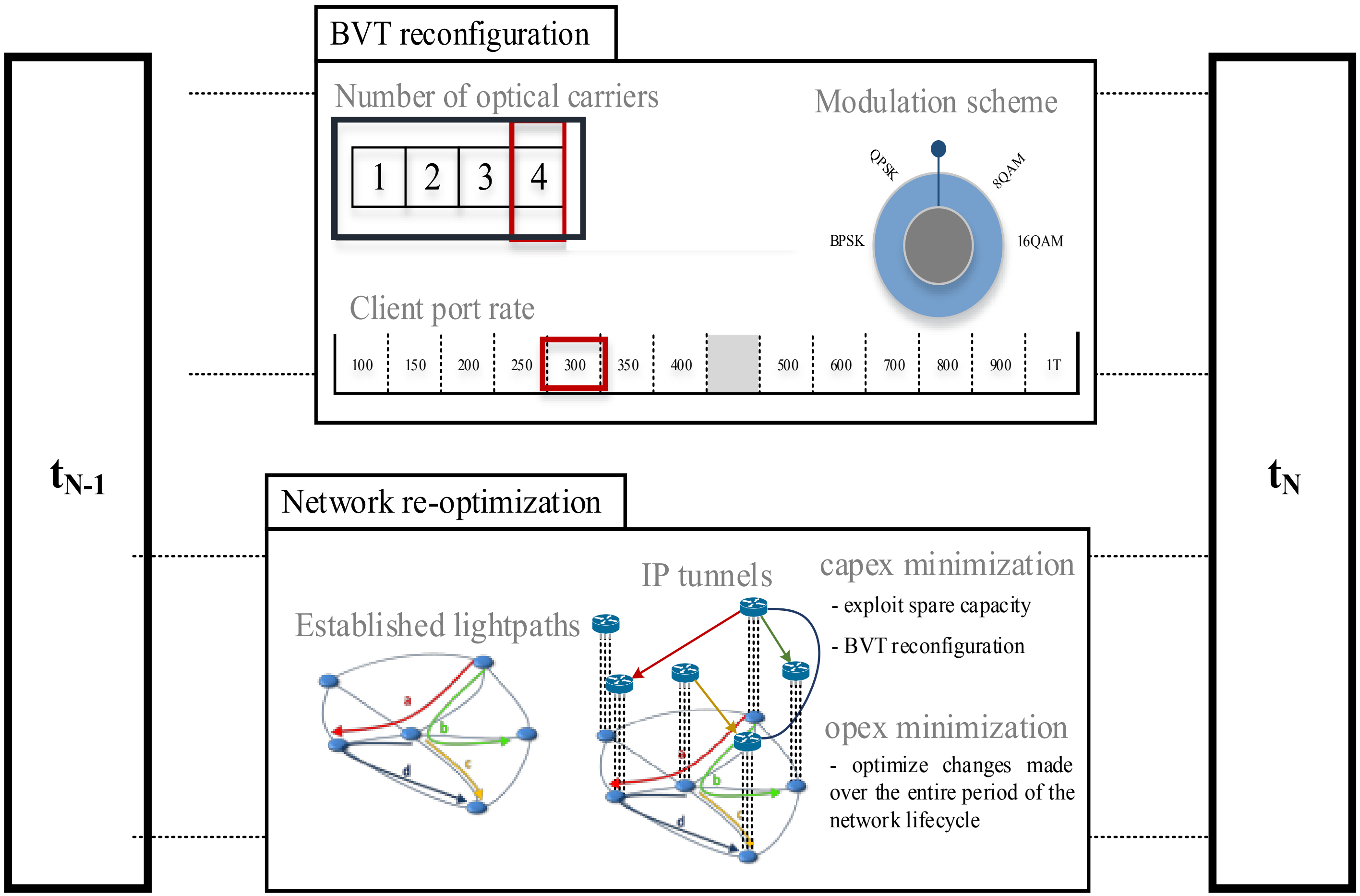
- new traffic demands
- previous state of the network at t_{N-1}
- state of the resources (established lightpaths and IP tunnels)
- information about physical resources (installed/available equipment and its location)

Objective

minimize:

- **CapEx** of **added** network equipment
- **Control the re-configuration** between the two successive network states (low disruption and manual interventions)

Incremental Multi-layer Network Planning (2/2)



Incremental model

- ☑ **flexibility** of **BVTs**
  different configurations to carry client traffic adapt transmission parameters
- ☑ **Flexibility of IP**
  exploit IP grooming capabilities to enable spare capacity utilization
- ☑ Exploit technology maturation **(depreciation)**
- ☑ Capture **traffic dynamicity**

Multi-period planning techniques

Technique I (reference): **Joint multilayer planning without previous state** (*J-ML*)

- Dimension each period from scratch (as if period is the initial) – lowest possible cost

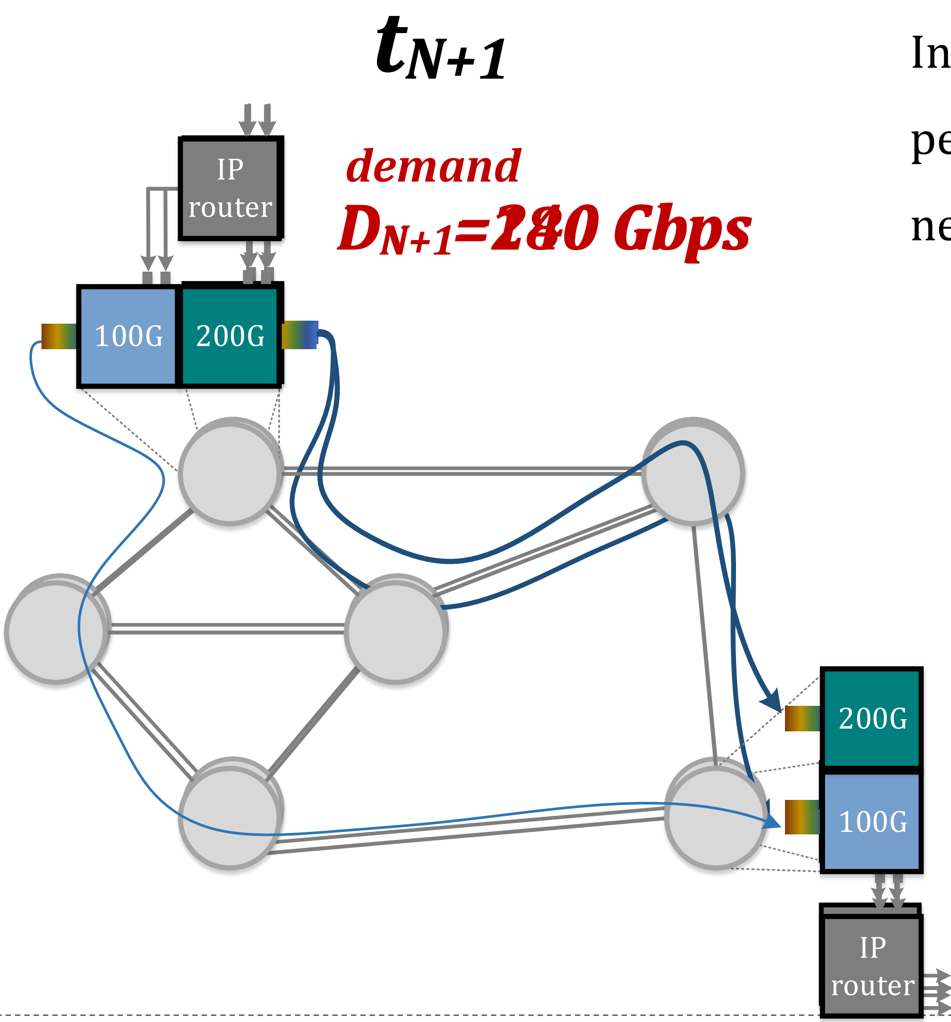
Technique II: **Incremental multilayer planning on top of the previous state** (*Inc*)

- Incremental dimensioning with no reconfiguration of transponders & IP equipment (maintain the previous network state)

Technique III: **Incremental multilayer planning with optimized adaptations**

- Allow but penalize the adaptations from the previous network state
- Study two variations:
  - Allow (for free) IP layer adaptations, forbid optical layer adaptations (*Inc-ML*)
  - Allow IP and allow but penalize optical layer adaptations (*J-Inc-ML*)

Transition between network states (1/3)

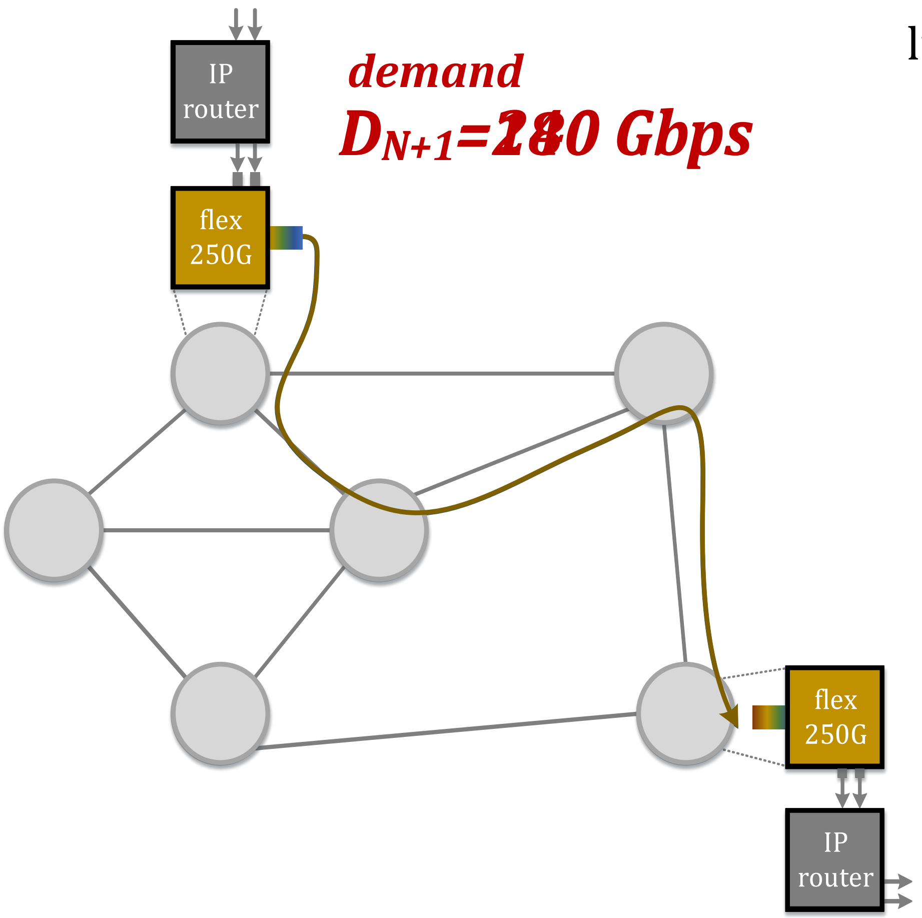


Incremental planning without being able to perform any change from the previous network state.

- ☒ **No** transponders and IP equipment **reconfigurations**
- ☒ capacity **overprovisioning**
- ☒ **underutilized** equipment
- ☒ **unnecessary investments**

Transition between network states (2/3)

t_{N+1}



demand

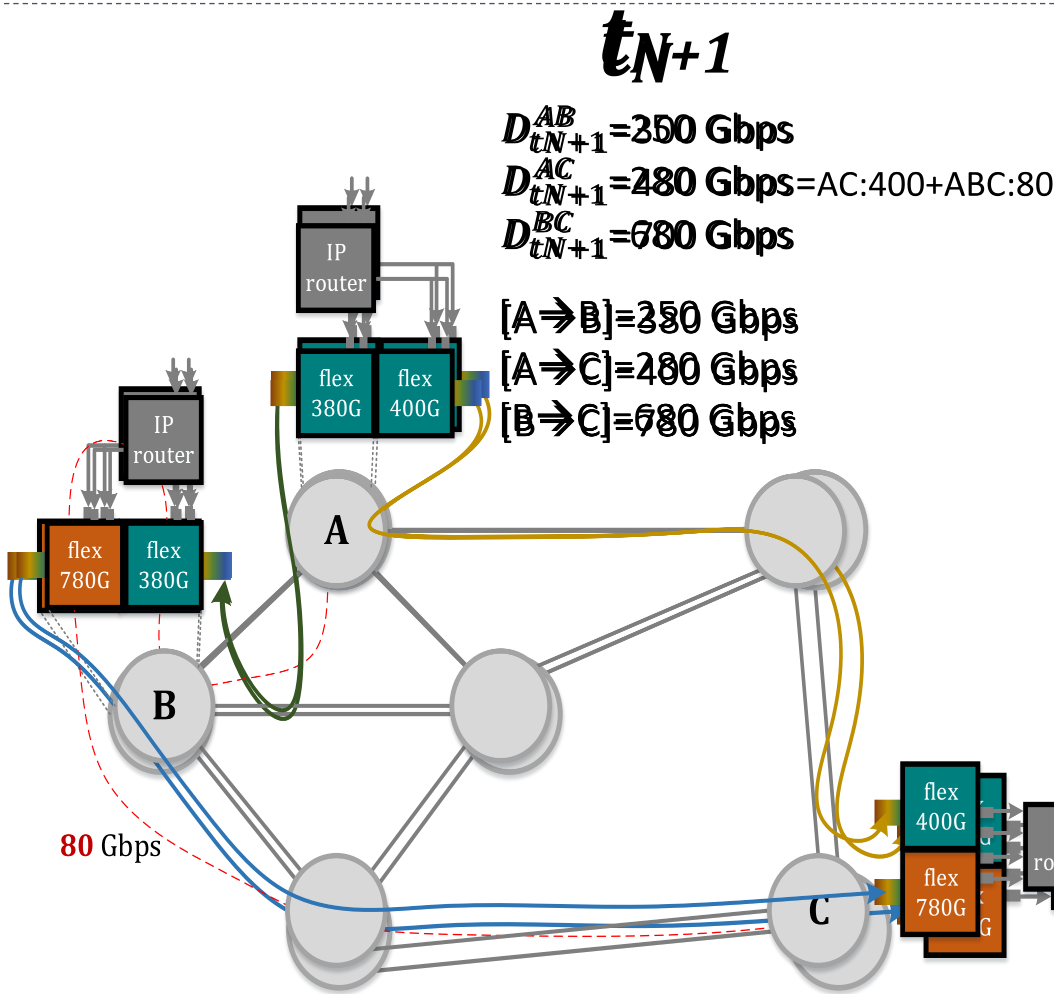
D_{N+1}=280 Gbps

Incremental multilayer planning optimizing lightpath reconfiguration between periods

☑ **flexibility** of **BVTs** and IP linecards

☑ **re-optimization** of the previous network state

Transition between network states (3/3)



Incremental multilayer planning optimizing modifications between periods

- ☑ **flexibility** of **BVTs**
- ☑ exploit **IP grooming capabilities** to enable spare capacity utilization
- ☑ **re-optimization** of the previous network state

ILP model

Input

- ❑ new traffic demands
- ❑ previous state of the network
- ❑ Weight to penalize the deviation from previous state

Constraints

- jointly consider multi-layer and incremental planning / detailed cost model for optical and IP equipment
- Penalize the reconfiguration of existing lightpaths, to control the extent of modifications performed between periods

Objective

Three-objective minimization
(CapEx, Spectrum, reconfigurations)

Input

- The network topology represented by graph $G(V,L)$.
- The maximum number Z of available spectrum slots (of 12.5 GHz)
- The traffic described by the traffic matrix Λ.
- A set B of the available transponders (BVTs).
- A set T of feasible transmission tuples, which represent the transmission options of the available transponders, with tuple $t=(D_t,R_t,S_t,C_t)$ indicating feasibility of transmision at distance D_t, with rate R_t (Gpbs), using S_t spectrum slots, for the transponder of cost C_t. Also, T_b represents the transmission tuples of transponder $b \in B$.
- A set of line-cards represented by H, where a line-card for transponder $b \in B$ is represented by a tuple $h_b=(N_h,C_h)$, where N_h is the number of transponders of type b that the line-card supports.
- The IP/MPLS router cost, specified by a modular cost model. We assume that an IP/MPLS router consists of line-card chassis of cost C_{LCC}, that suport N_{LCC} line-cards each, and fabric card chassis of cost C_{FCC}, that suport N_{FCC} line-card chassis.
- The weighting coefficient, W_C, taking values between 0 and 1. Setting $W_c = 1$ minimizes solely the cost whereas setting $W_c \approx 0$ minimizes the maximum spectrum used.
- The weighting coefficient, W_d, taking values between 0 and 1. Setting $W_d = 1$ minimizes solely the current state cost ignoring the previous network state, whereas setting $W_d \approx 0$ maintains the previous state lightpaths and minimizes any additional cost to that.

Variables

- f_{sd}^p: Float variables, equal to the rate of the IP tunnel from IP source s to destination d that passes over a lightpath that uses path p.
- x_{pt}: Integer variables, equal to the number of lightpaths of path-transmission tuple pairs (p,t) used.
- y_{nh}: Integer variables, equal to the number of line-cards of type h at node n.
- q_n: Integer variables, equal to the number of line-card chassis at node n.
- o_n: Integer variables, equal to the number of fabric-card chassis at node n.
- z: Integer variable, equal to the maximum indexed spectrum slot.
- θ_{nb}: Integer variables, equal to the number of utilized transponders of type b at node n.
- v_{nb}: Integer variables, equal to the number of deployed transponders of type b at node n.
- d_{pt}: Integer variables, equal to the number of removed (p,t) tuples from the previous state.
- c: Float variable, equal to the cost of network equipment.

Constants

- $F_{sd}^{'p}$: Integer constants, equal to the IP traffic of end-nodes s to d that is transferred over optical path p in the previous network state.
- X'_{pt}: Integer constants, equal to the number of lightpaths of path-transmission tuple pairs (p,t) used in the previous network state.
- θ'_{nb}: Integer constants, equal to the number of transponders of type b at node n used in the previous network state.

Objective

$$\min\left(W_C \cdot c + (1-W_C)\cdot z\right)$$

Cost calculation constraints:

$$c = W_d \cdot \Big(\sum_{n\in V}\sum_{b\in B} C_b \cdot v_{nb} + \sum_{n\in V}\sum_{h\in H} C_h \cdot y_{nh} + \sum_{n\in V} C_{LCC}\cdot q_n + \sum_{n\in V} C_{CH}\cdot o_n\Big) + (1-W_d)\cdot \sum_{p\in P}\sum_{t\in T|\exists(p,t)} d_{pt}$$

IP flow continuity constraints:

$\forall\ (s,d)\in V^2, n\in V$

$$\left(\sum_{i\in V}\sum_{p\in P_{in}} f_{sd}^p - \sum_{j\in V}\sum_{p\in P_{nj}} f_{sd}^p\right) = \begin{cases} -\Lambda_{sd},\ n=s \\ \Lambda_{sd},\ n=d \\ 0,\quad n\neq s,d \end{cases}$$

Path-transmission tuple assignment constraints:

$\forall\ (i,j)\in V^2$

$$\sum_{sd\in V^2} f_{sd}^p \le \sum_{p\in P_{ij}}\sum_{t\in T|\exists(p,t)} (R_t \cdot x_{pt})$$

Previous state constraints (*optical layer*):

$\forall\ \ feasible(p,t)$

$$d_{pt} \ge X'_{pt} - x_{pt}$$

Maximum spectrum slot used constraints:

$\forall\ l\in L, (i,j)\in V^2,$

$$z^l = \sum_{p\in P_{ij}|l\in p}\ \sum_{t\in T|\exists(p,t)} (S_t \cdot x_{pt})$$

$$z = \max\left(z^l\right)$$

$$z \le Z$$

Previous state constraints (*IP layer*):

$\forall\ (s,d)\in V^2, (i,j)\in V^2, p\in P_{ij}\ |\ F'^p_{sd} > 0,$

$$f_{sd}^p > F'^p_{sd}$$

Utilized transponders constraints:

$\forall\ n\in V, b\in B$

$$\theta_{nb} = \sum_{p\ starts\ at\ n}\ \sum_{t\in T_b} x_{pt}$$

Deployed transponders constraints:

$\forall\ n\in V, b\in B$

$$v_{nb} \ge \theta_{nb}$$

$$v_{nb} \ge \Theta'_{nb}$$

Number of line-cards per node constraints:

$\forall\ n\in V, h\in H$

$$y_{nh} \ge \sum_{b \text{ is supported by } h} v_{nb} / N_h$$

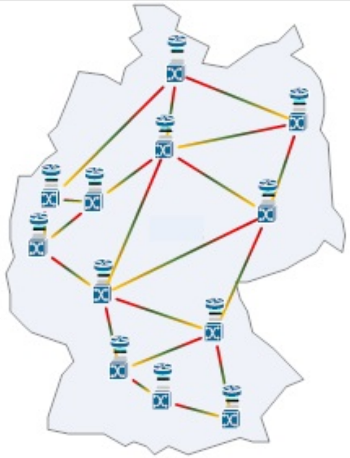
Number of line-card chassis per node constraints:

$$q_n \ge \sum_h y_{nh} / N_{LCC}\ ,\ \forall n\in V$$

Number of fabric card chassis per node constraints:

$$o_n \ge q_n / N_{CH}\ ,\ \forall n\in V$$

Illustrative results - Scenario



Operator	Location		Segment Covered		
DT	**Germany**		**Core**		
Nodes	Nodal Degree		Links	Link length *(km)*	
	average	max		average	max
12	**3**	**5**	**40 *bidirectional***	**243**	**459**

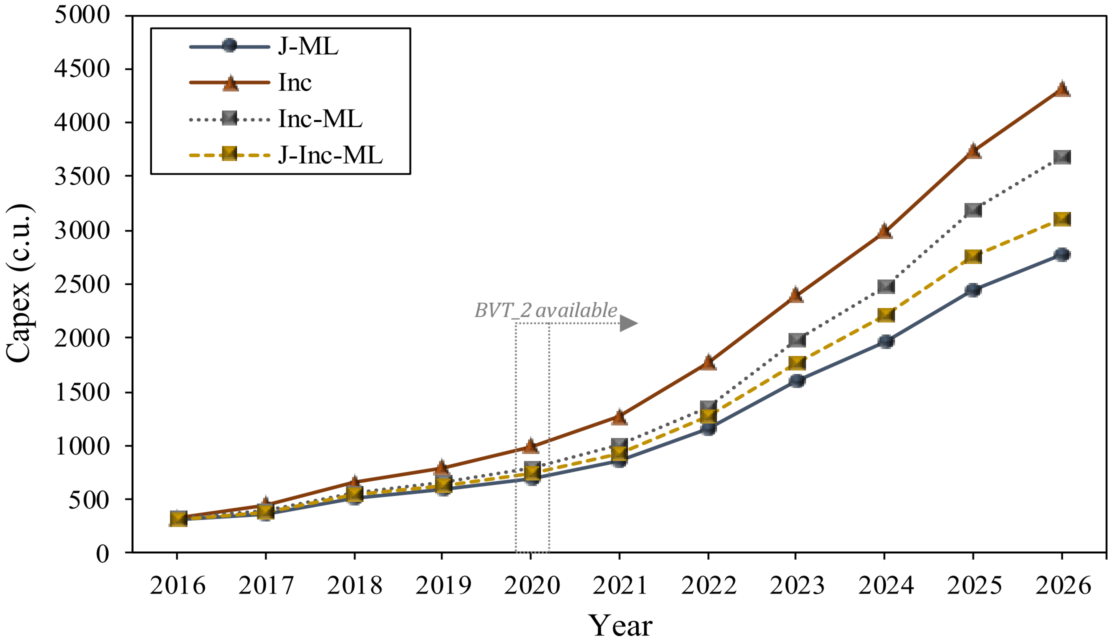
- DT topology, 2012 traffic, uncompensated links, 12.5 GHz slots
- Incremental planning for 2016-2026 - yearly
- Traffic increase by 35% uniformly per year
- 2 types of BVTs/regens *(i)* ***400 Gbps***, *(ii)* ***1 Tbps***, *available at 2020*
- 10% price depreciation per year
- Objective: weighted minimization of Capex, reconfigurations, spectrum
  - 80% CaPex, 10% reconfigurations, and the rest 10% spectrum

BVT 1				BVT 2			
Capacity (Gb/s)	Reach (km)	Data slots	cost (c.u.)	Capacity (Gb/s)	Reach (km)	Data slots	cost (c.u.)
100	2000	4		**500**	950	7	
150	1350	4		**600**	800	8	
200	1050	5		**700**	700	9	2*
250	950	5	1.76	**800**	650	11	
300	700	6		**900**	550	12	
350	600	6		**1000**	450	14	
400	450	6		**available from 2020*			

ILP termination

- Integer gap tolerance: 0.05

Illustrative Results (1/2)



J-ML: Joint multilayer planning without previous state *(benchmark- minimum)*

Inc: Incremental multilayer planning on top of existing state *(no adaptation of optical and IP equipment)*

Inc-ML: Incremental multilayer planning (*allow for free IP layer adaptation, no adaptation of optical layer)*

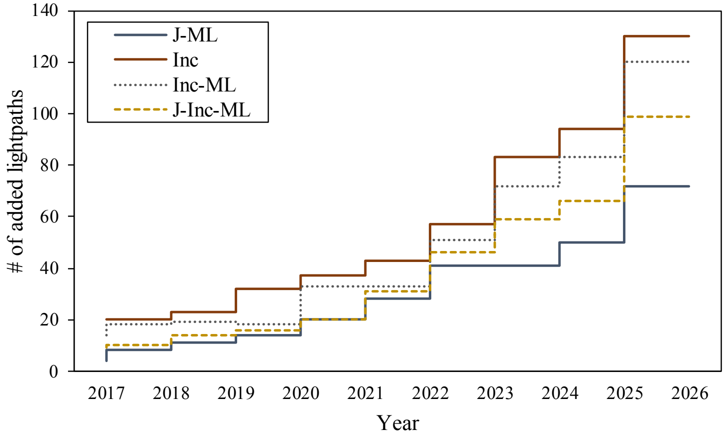
J-Inc-ML: Incremental multilayer planning (*penalize IP and optical adaptations*)

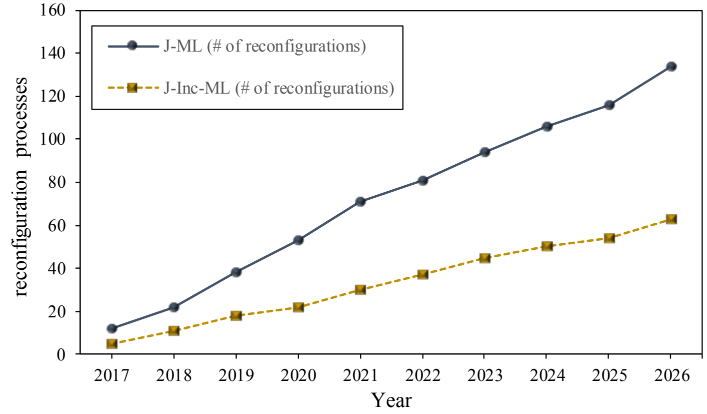
- ***J-ML*** : the minimum CaPex, as if the network was planned from scratch on each year
- ***Inc***: exhibits the worst performance, due to the inability to exploit IP & optical equipment reconfigurations
- ***Inc-ML*** : exploits reconfiguration capabilities of IP layer to achieve cost savings
- ***J-Inc-ML***: exploits reconfiguration capabilities of both layers and achieves even higher cost savings

***1 c.u.**: cost of a 100 Gb/s coherent optical transponder*

Illustrative Results (2/2)

- **Challenge:** optimize the reconfigurations made together with the minimization of the cost





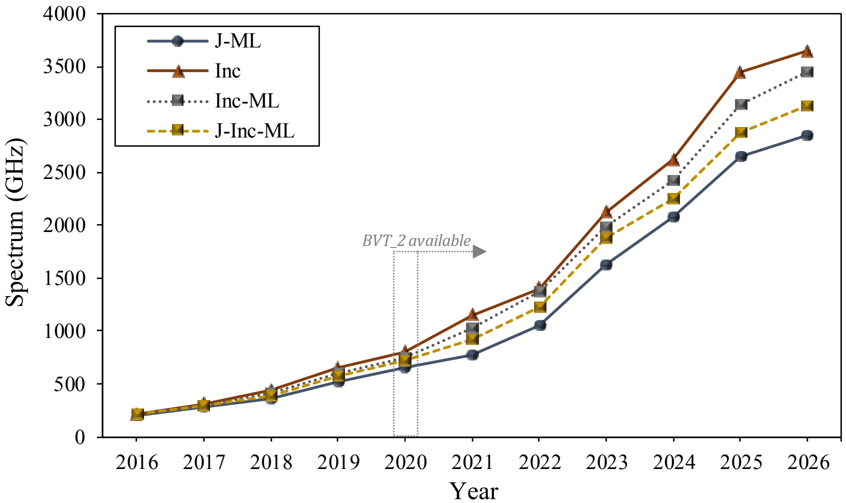
Trade-off between the added equipment and reconfigurations between consecutive network states

Spectrum Utilization

- ***J-Inc-ML*** also achieves spectrum savings

The savings are slightly lower compared to CapEx due to deployment of more regenerators* for *Inc* and *Inc-ML*

*(*regenerators provide wavelength conversion possibilities*)

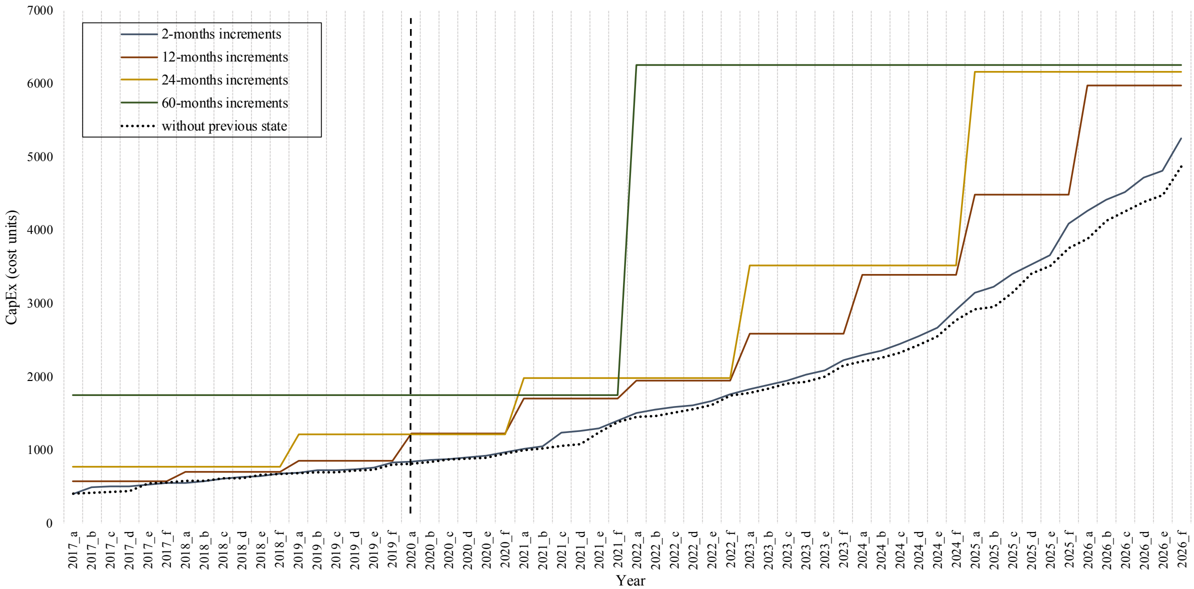


Extended models *Work in progress*

cost vs network upgrade cycles

2-months vs multi-year

network upgrade cycles



Short network cycles:

- ☑ are able to capture the effects of **traffic dynamicity** and **avoid overprovisioning** *(small but frequent network updates)*
- ☑ postpone the investments and exploit technology maturation

Conclusions

- Long and independent (*between network layers*) upgrade cycles lead to capacity overprovisioning, underutilized equipment and unnecessary investments
- Shorter upgrade cycles and joint multi-layer upgrades increase the network efficiency, operate the network closer to its true capabilities, and postpone or avoid investments
- ILP model that combines multi-layer and incremental planning and tradeoffs:
  - the capital expenditure (CapEx) of the added equipment at both layers
  - the reconfigurations for the transition between two consecutive periods

Questions ?