An introduction to routing and wavelength assignment algorithms for fixed and flexgrid

Emmanouel (Manos) Varvarigos

Computer Engineering and Informatics Department, University of Patras, and
Computer Technology Institute & Press "DIOPHANTUS", Patra, Greece

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Network optimization problems

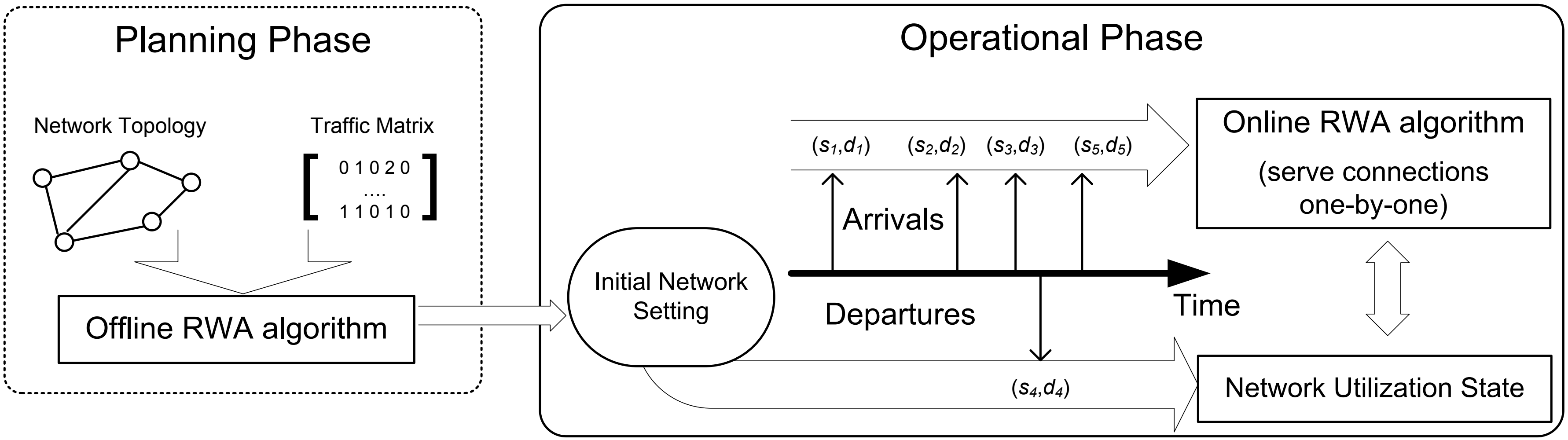
- Network optimization problems
  - Simple : shortest-path, max-flow, minimum spanning tree …
  - Difficult (hard): integer multicommodity flow, graph coloring, traveling salesman, Steiner trees …
- Optimization problems encountered in Optical Core Networks
  - Most of them are difficult!
  - Network planning and operation: resource allocation problems

    resources= space (transponders, regenerators, cross-connections, links, fiber-cores), frequency (wavelengths or spectrum slots), time
  - Routing and Wavelength Assignment (RWA) & impairment-aware RWA
  - Routing and Spectrum Allocation (RSA) & Modulation Level, and Spectrum allocation (RMLSA)
  - Traffic grooming, time scheduling, hierarchical clustering of nodes, etc

Complexity

- Which algorithm is efficient? How do we define efficiency?
- Time and Space Complexity
- "worst case" vs. "actual case"
- Efficient ≡ polynomial time algorithms: the number of primitive operations that is needed to obtain the solution for any input instance *I* of the problem is bounded by a polynomial on the size of the input *I*
- Not efficient ≡ non-polynomial (exponential) algorithms
- A problem is provably "difficult" or "hard" if it belongs to the class of NP-complete problems, for which no polynomial time algorithms are known

Planning and operating optical networks



- Planning phase (offline – static RWA)

  Simultaneously optimize all connections (Combinatorial optimization)

- Network Evolution - Operational phase (online –dynamic RWA)

  Serve one or a set of connections – Re-optimize

In this tutorial

- Present general algorithms and techniques that can be used to solve network optimization problems
- Focus on resource allocation problems in standard WDM and flexgrid optical networks and present examples of applying the general techniques to solve the specific problems

Outline

- Generic optimization methods
  - Linear Programming, Integer Linear Programming
  - Meta-heuristics
  - Heuristics
- Standard WDM networks
  - Planning
  - Physical layer impairments
  - Network evolution
- Flexgrid optical networks
  - Planning
  - Physical layer impairments
  - Network evolution

Linear Programming (LP)

Linear Optimization (LP) Problem

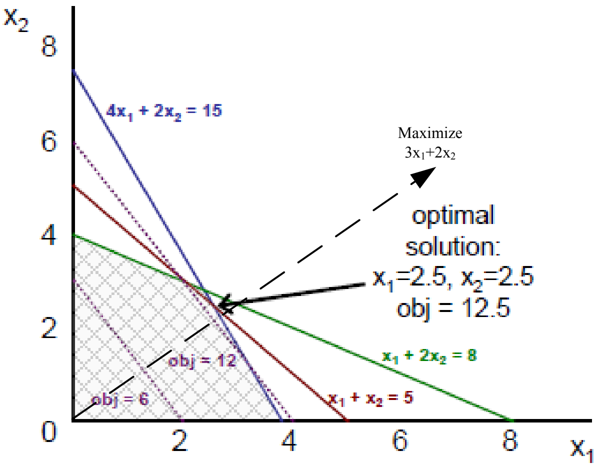
minimize $c^T \cdot \boldsymbol{x}$

subject to $A \cdot \boldsymbol{x} \leq b$, $\mathbf{x} = (x_1,\ldots,x_n) \in \mathrm{R}^n$,

where *c* is a *n*-dimension vector, *A* is a *mxn* matrix, and *b* is a *m*-dimension vector

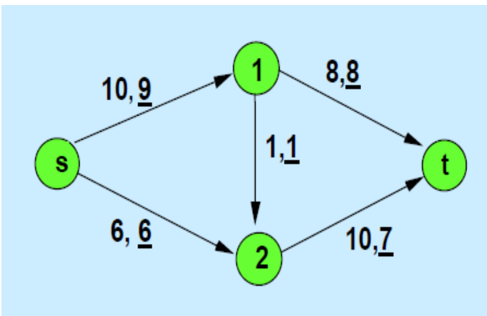
- Linear objective and linear constraints
  - Local minimum is also a global minimum
  - The solution space is a *n*-dimension convex polyhedron
  - The optimal solution (minimum) is a vertex of the polyhedron
- LP problems are solvable in polynomial time
  - Simplex (exponential time worst case), Ellipsoid algorithm (first polynomial), Interior point algorithm
  - Simplex is vastly used (good average running time)

$$\begin{aligned}&\text{maximize } 3x_1 + 2x_2\\&\text{subject to}\\&4x_1 + 2x_2 \leq 15\\&x_1 + 2x_2 \leq 8\\&x_1 + x_2 \leq 5\\&x_1 \geq 0; x_2 \geq 0\end{aligned}$$



LP modeling of simple problems

Maximum Flow



Input:
Demand (s,t),
Link capacities u_{ij}

Variables:
x_{ij} flow over link (i,j)

Maximize v
Subject to

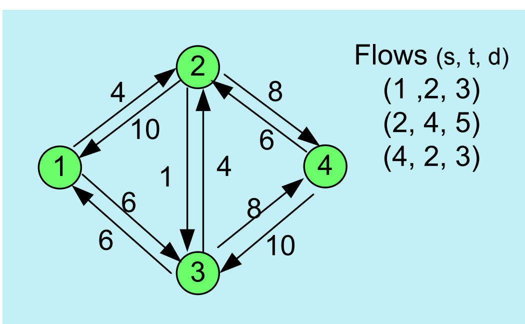
$$\sum_j x_{sj} = v$$

$$\sum_j x_{ij} - \sum_j x_{ji} = 0, \text{for all } i \neq s \text{ or } t$$

$$\sum_i x_{it} = -v$$

$$0 \leq x_{ij} \leq u_{ij}, \text{for all links } (i, j)$$

Multicommodity Flow



Input:
Flows $f \rightarrow (s_f,t_f,d_f)$,
Link capacities u_{ij}

Variables:
x_{ij}^f flow of f over link (i,j),
$x_{ij}^f \in R$

Minimize 0
Subject to

$$\sum_f x_{ij}^f \leq u_{ij} \text{ for all links } (i, j)$$

$$\sum_j x_{s_f j}^f = d_f \text{ for all flows } f$$

$$\sum_i x_{i t_f}^f = -d_f \text{ for all flows } f$$

$$\sum_i x_{ij}^f = \sum_k x_{jk}^f \text{ for all } j \neq s_f, t_f$$

What if we ask for integer flows;

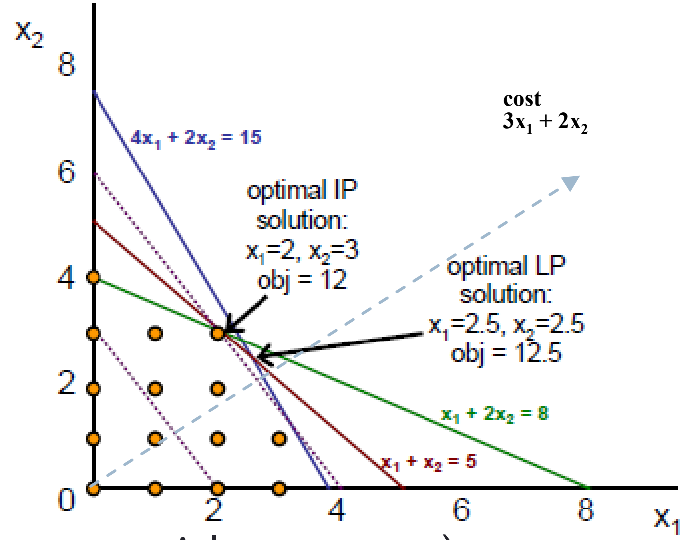
Integer Linear Programming (ILP)

- Integer variables ***x***

  minimize $c^T \cdot \boldsymbol{x}$

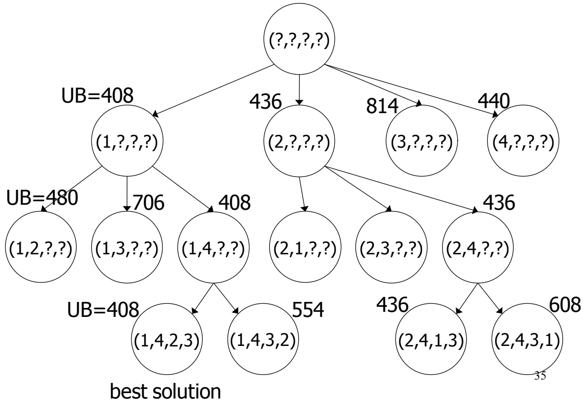
  subject to $A \cdot \boldsymbol{x} \leq b$, $\mathbf{x} = (x_1,\ldots,x_n) \in Z^n$

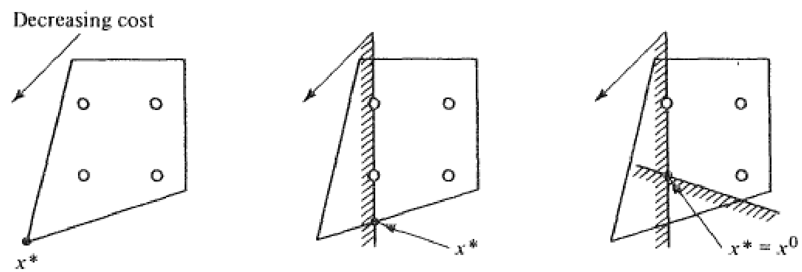
- The general ILP problem is NP-complete
- Exhaustive search



Techniques to improve average exec time (but still exponential worst case)

Branch-and-bound, Cutting planes





LP and ILP relation

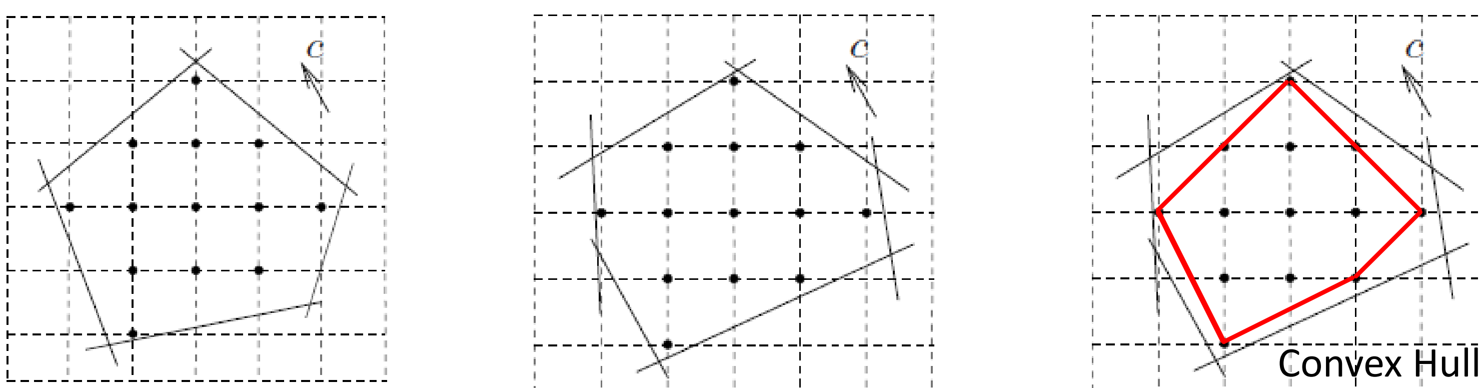
- Assume a "difficult" ILP problem
- *LP-relaxation*: solve the ILP without demanding integer variables
  - Can be solved in polynomial time
  - Gives the lower (upper) bound for the ILP minimization (maximization) problem. Branch & bound technique uses this feature
  - If the solution is integer, then it is optimal for the initial ILP problem

    Luck ?

    Hint: there are certain techniques and rules to write LP formulations that can increase the probability to obtain an integer solution
  - If integer-optimal is not found: rounding methods, such as randomized rounding, can yield good approximate solutions

Convex Hull

- The same set of integer solutions can be described by different sets of constraints
- *Convex hull:* the minimum convex set that includes all the integer solutions
- Given the convex hull, an LP algorithm can obtain the optimal ILP solution in polynomial time
- The transformation of an *n*-dimension polyhedron to the corresponding convex hull is difficult (used in cutting planes technique)
- *Good ILP formulation:* the feasible region defined by the constraints is tight to the convex hull
  - A large number of vertices consist of integer variables: increases the probability of obtaining an integer solution when solving the corresponding LP-relaxation of the initial ILP problem



The same set of integer solutions can be included in different-shaped feasible regions

Meta-heuristics

- Iteratively try to improve a candidate solution with regards to a given metric
- Do not guarantee to find an optimal, as opposed to exact methods (like ILP)
- A meta-heuristic typically defines:
  - The representation or encoding of a solution
  - The cost function
  - Iterative procedure
- Meta-heuristic types
  - Local search: iteratively make small changes to a single solution
  - Constructive: construct solutions from their constituting parts
  - Population-based: iteratively combine solutions into new ones

  However, these classes are not mutually exclusive and many algos combine them
- Popular meta-heuristics: Genetic/evolutionary algorithms, ant colony optimization, tabu search, simulated annealing

Heuristics

- Heuristic: simple, fast, and can find *good enough* solutions
  - Depending on the problem, a heuristic can be optimal
    (but not for the majority of problems that we face)
  - Greedy : at each step make a choice that seems good (towards a local optimum), with the hope of finding a global optimum
- Combinatorial problems can be solved by allocating resources one-by-one to demands
  - Routing problems: shortest-path, k-shortest paths (weight= #hops, or distance)
  - Wavelength assignment: random, first-fit, least used, most used wavelength
  - Slot assignment: similar to wavelength assignment, but can take into account the size of voids created

Single and Multi-objective optimization

- Most problems are formulated as single-objective optimization problems

  e.g. minimize #transponders, **or** # wavelengths, **or** energy consumption, etc.
- What if we want to optimize more than one metric

  e.g. minimize both the #transponders **and** #wavelengths
  - No single solution simultaneously accomplishes the two
  - Non-dominated or Pareto front: the set of solutions that cannot be improved in one objective without deteriorating their performance in at least one of the rest

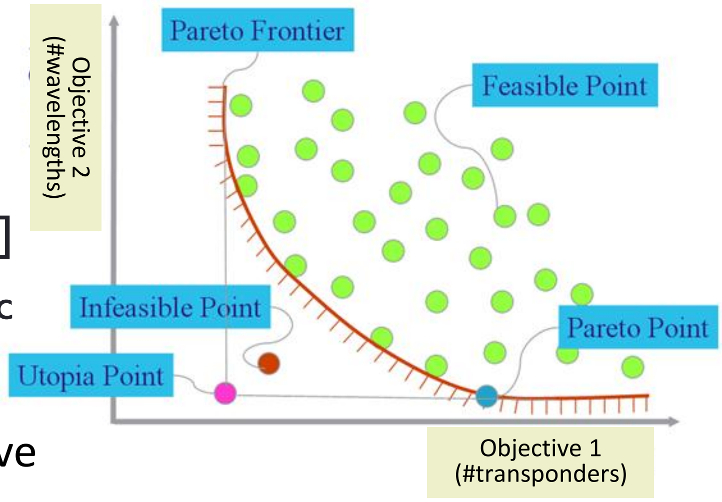
- Use single objective methods

  Scalarizing: use a single-objective defined as a weighted combination of the multi-objectives

  minimize: (w · #transponders) + [(1- w) · # wavelengths)]

  weighing coefficient w controls the dependence on each metric
- Use multi-objective methods

  types: no preference, a priori, a posteriori and interactive



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  - Meta-heuristics
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  - Physical layer impairments
  - Network evolution
- Flexgrid optical networks
  - Planning
  - Physical layer impairments
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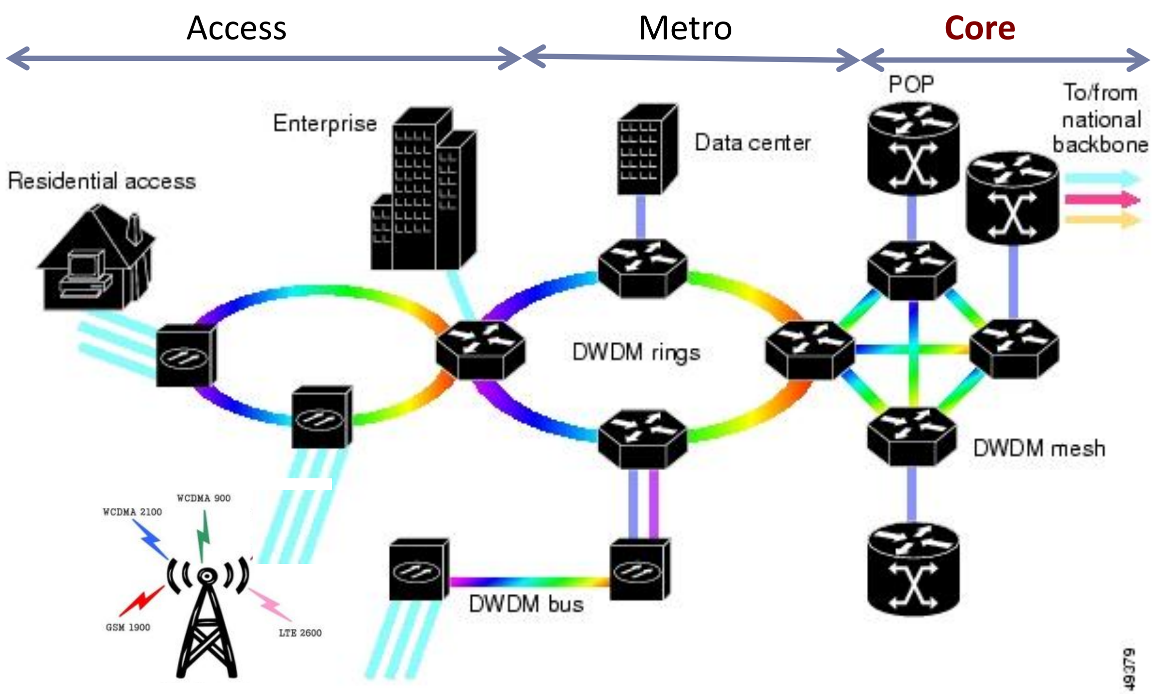
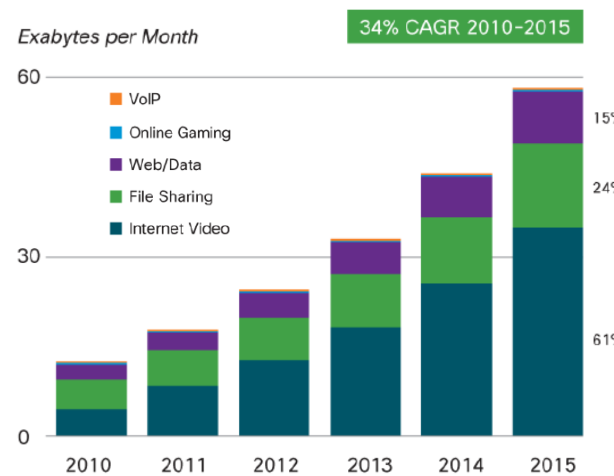
Motivation



Capacity Increase

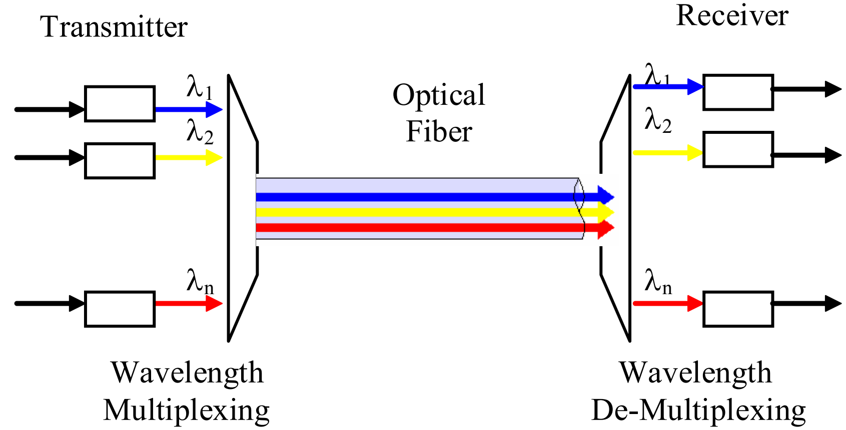
(Cisco's Visual Networking Index)



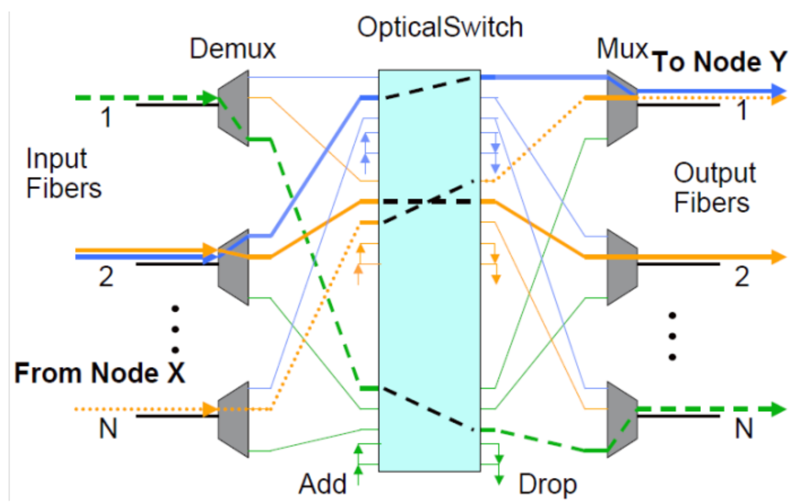
- Improve efficiency of current systems through better resource allocation
- Algorithms for next generation systems (higher rate WDM, MLR WDM, flexgrid)

WDM optical networks

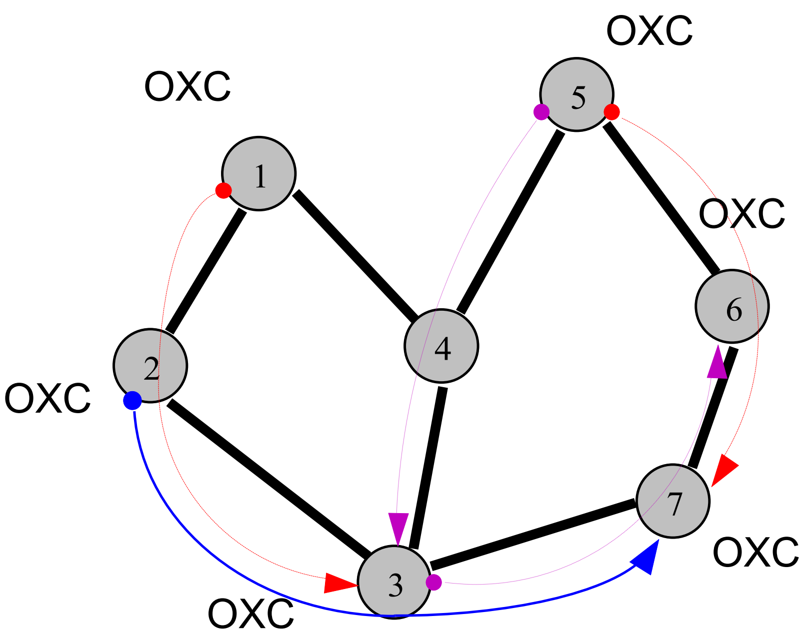
Wavelength Division Multiplexing (WDM)



- WDM switches
  - Switched entity: wavelength
  - Opaque (OEO)
  - Transparent (OOO)
  - Reconfigurable add-drop multiplexers (ROADM)

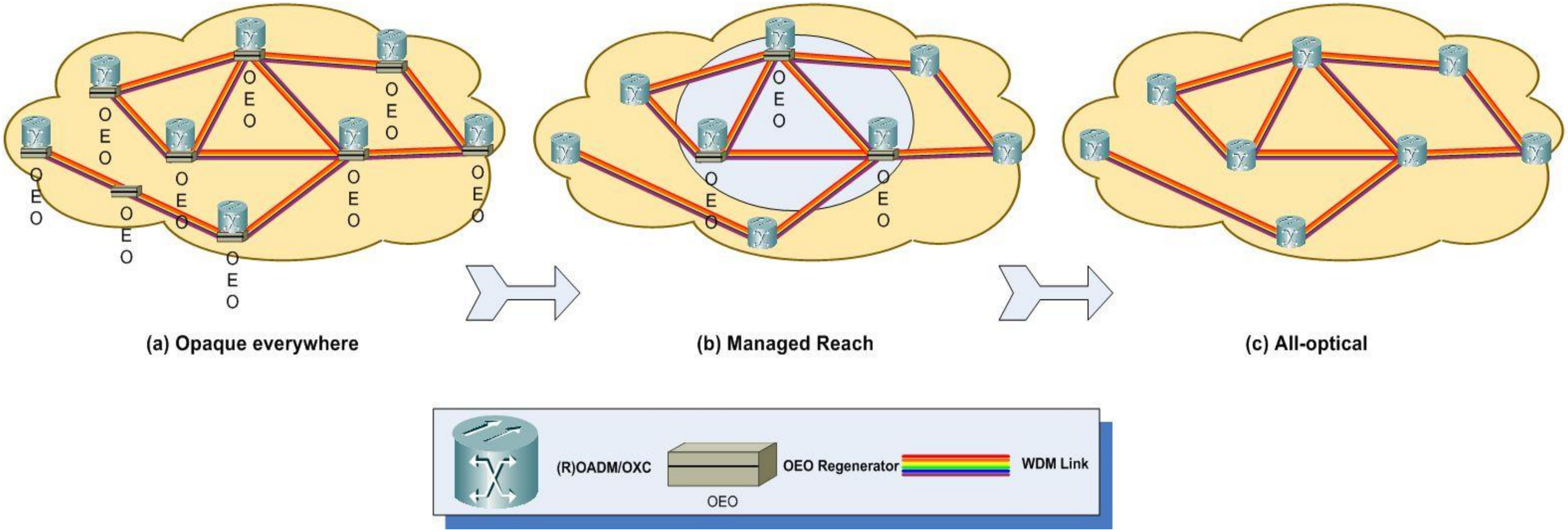


Lightpaths



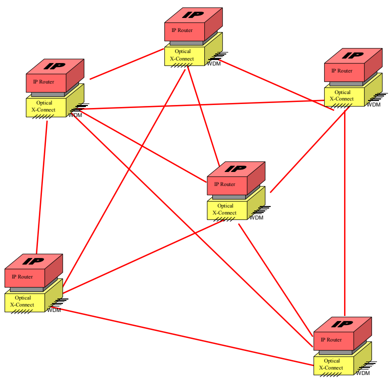
- WDM: communication through lightpaths
- Lightpath:
  - Route (path)
  - Wavelength
- Discrete wavelength assignment
- Wavelength continuity
  (when no wavelength conversion is available)
- Routing and Wavelength Assignment (RWA)

WDM networks evolution



- Past: *Opaque* (point-to-point) – Transponders at each node
- Move from *Opaque* to *Transparent* networks. Reduce the transponders
  - ☑ Gains in cost (CapEx and OpEx)
  - ☒ Transparent lightpaths: physical layer impairments
- Solution
  - ☑ Impairment aware routing and wavelength assignment (IA-RWA)

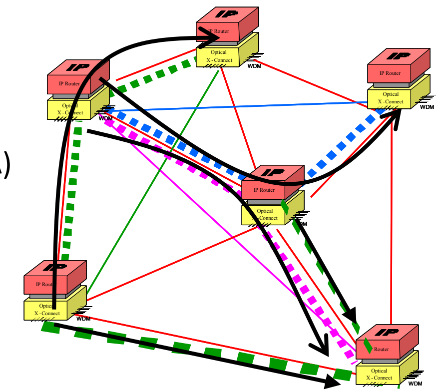
Planning WDM networks



+

$$\begin{bmatrix} 0 & 1 & 2 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 2 & 0 \\ 2 & 1 & 0 & 1 & 0 & 1 \\ 0 & 2 & 1 & 1 & 1 & 0 \end{bmatrix}$$

Routing and Wavelength Assignment (RWA)



- Input: Network topology, traffic matrix
- Output: routes and wavelengths (RWA)
  - **Network layer**: Satisfy traffic and minimize the number of used wavelengths
- Constraints:
  - Discrete wavelength assignment
  - Wavelength continuity

RWA algorithms

- Joint RWA or decomposed R+WA
- Joint RWA ILP formulations: path and link formulations
  - Path formulation

    Pre-calculate all or a set of paths for each demand

    Variable: $x_{p,w}$ is 1 if the specific path p and wavelength w is selected

    Constraints: flow constraints only at source node, discrete wavelength assignment constraints, no need for wavelength continuity constraints
  - Link formulation

    Variables: x_{dlw} is 1 if demand d is served by link l and wavelength w

    Constraints: flow constraints at source & intermediate & destination nodes, (including wavelength continuity), discrete wavelength assignment constraints,

	# of variables	# of constraints
Link	$O(N^3W)$	$O(N^3W)$
Path	$O(N^2W)$	$O(NW)$

Although path formulation seems more efficient, extensions of the RWA problem (e.g. regeneration placement) might need link-related variables

- Large number of meta-heuristics and heuristics in the literature

Physical Layer Impairments (PLI)

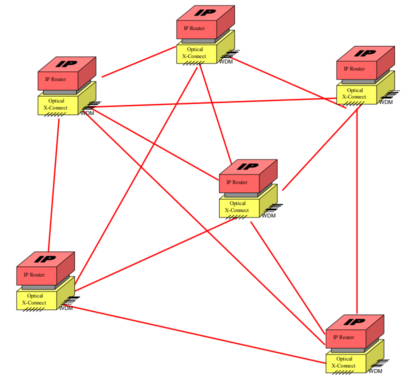
- Linear and non-linear PLI impairments
- Interest from an algorithmic perspective:

  Intra-lightpath or inter-lightpath (interference)
  - Intra-lightpath PLIs: ASE, PMD, CD, SPM
  - Interference PLIs: intra-and inter-channel XT, XPM, FWM
- Depend on modulation format, transponder technology, etc.
- Coherent transponders compensate for chromatic dispersion (CD)
- Lightpath feasibility: Quality of Transmission (QoT)
  - Use threshold(s) to judge the feasibility of lightpaths
  - Separate metric for each PLI
  - Single metric: Bit Error Ratio (BER), Q factor

RWA + physical layer

Input:

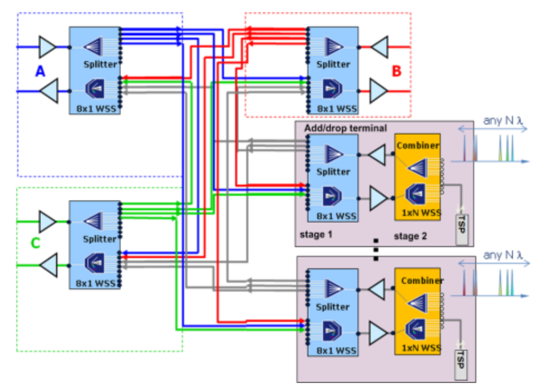
Network topology, traffic matrix,
Physical layer models and parameters
(link and OXC model)

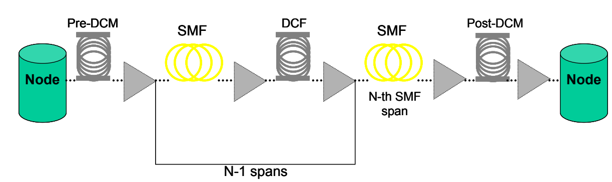


$$\begin{bmatrix} 0 & 1 & 2 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 2 & 0 \\ 2 & 1 & 0 & 1 & 0 & 1 \\ 0 & 2 & 1 & 1 & 1 & 0 \end{bmatrix}$$

- Output: routes and wavelengths
  - **Network layer** - RWA: Satisfy traffic and minimize the number of used wavelengths
  - **Physical layer -** IA: use lightpaths with acceptable quality of transmission

→IA-RWA cross-layer optimization

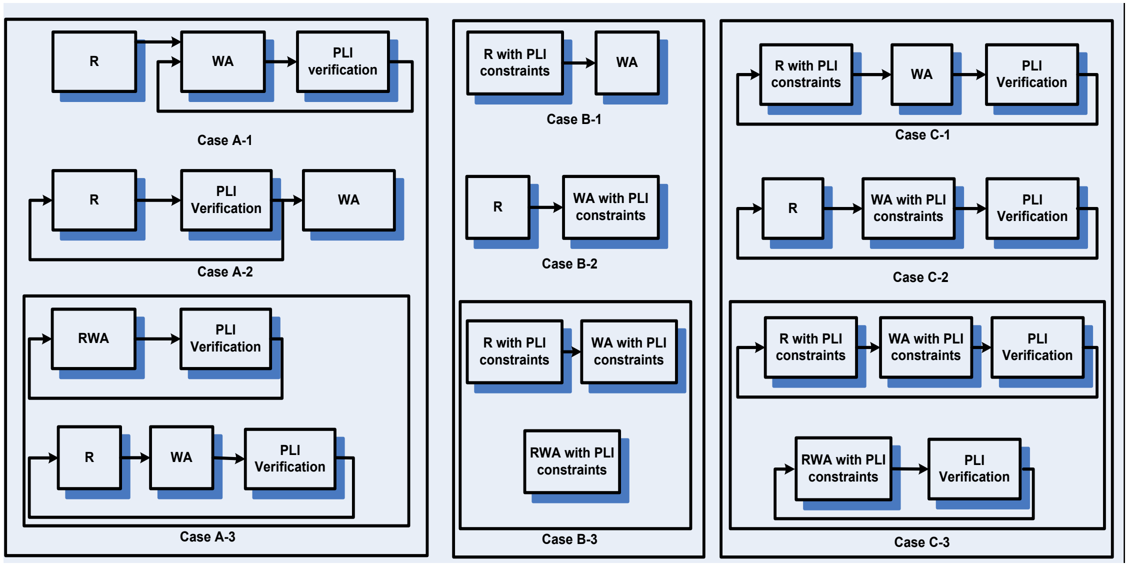




IA-RWA algos classification

Based on where IA is applied

- RWA + (separate) PLI verification module
- IA in either R or WA
- Joint IA-RWA (IA in RWA formulation)



Based on how PLIs are accounted for

- Indirect

e.g. constraint the path length, # of hops

- Direct

e.g. use analytical models for ASE

- Worst-case assumption

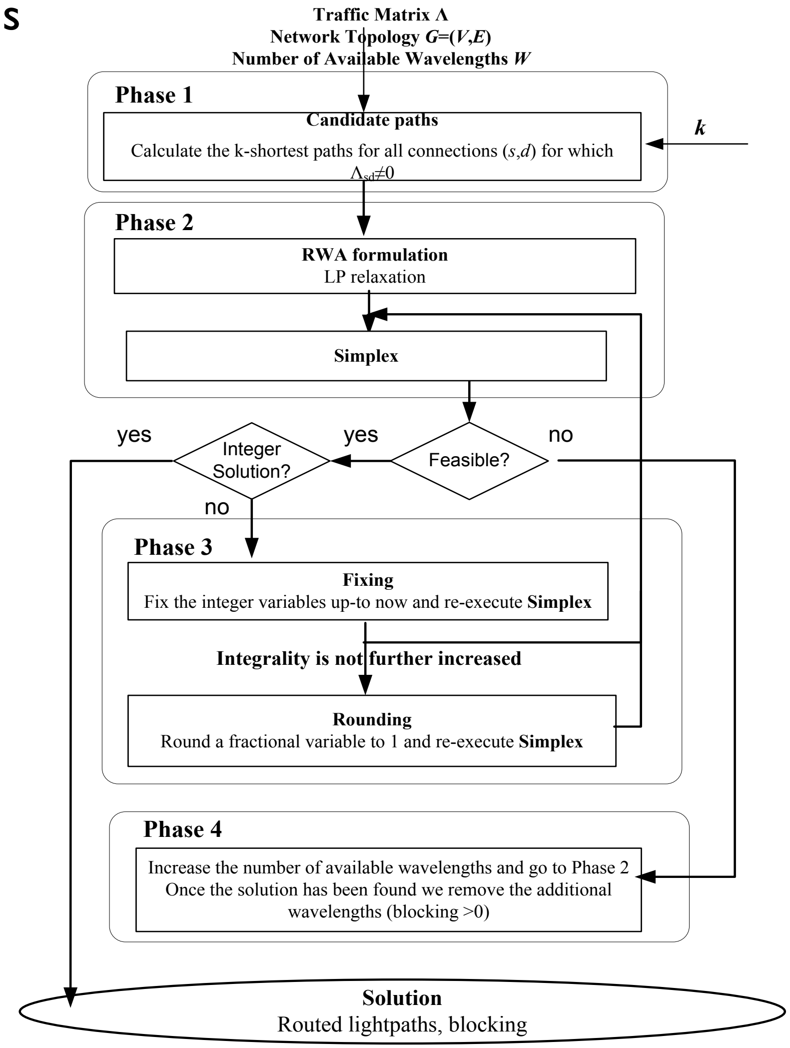
calculate PLIs as if all wavelengths are utilized

- Actual case

calculate PLIs based on the lightpaths that are (or will be) established

IA-RWA algorithm example

- Input: topology, traffic matrix, link and OXC models
- Output: lightpaths that are QoT feasible
- Algo: based on LP-relaxation, path formulation, direct IA, actual case, IA in the formulation
- RWA need integer variables (ILP): **NP-complete** (lightpaths cannot bifurcate)
- LP-relaxation - float variables: **P**
  - ☑ Integer solution → optimal !
  - ☒ Fractional solution → rounding → maybe suboptimal
- Proposed LP-relaxation formulation
  - ☑ optimal integer solution with high probability
    - Piecewise linear cost function
    - Random perturbation technique



LP formulation and flow cost function

Parameters:

- $s,d \in V$: network nodes
- $w \in C$: an available wavelength
- $l \in E$: a network link
- $p \in P_{sd}$: a candidate path

Constant:

- Λ_{sd}: the number of requested connections from node s to d

Variables:

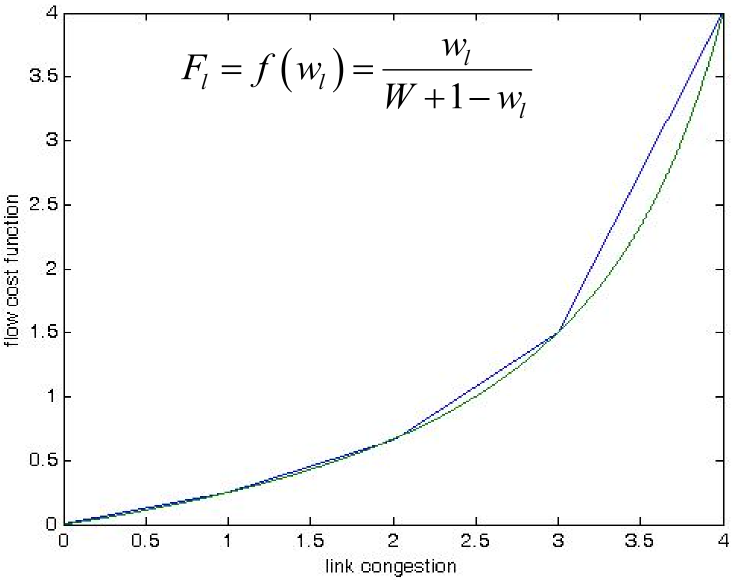
- x_{pw}: an indicator variable, equal to 1 if path p occupies wavelength w, else 0
- F_l: the flow cost function value of link l

RWA LP FORMULATION

$$\textbf{minimize}: \sum_l F_l$$

subject to the following constraints:

- Distinct wavelength assignment constraints,
$$\sum_{\{p|l\in p\}} x_{pw} \leq 1, \text{ for all } l \in E, \text{ for all } w \in C$$
- Incoming traffic constraints,
$$\sum_{p\in P_{sd}} \sum_{w} x_{pw} = \Lambda_{sd}, \text{ for all } (s,d) \text{ pairs}$$
- Flow cost function constraints,
$$F_l \geq f(w_l) = f\left(\sum_{\{p|l\in p\}} \sum_{w} x_{pw}\right)$$
- The integrality constraint is relaxed to
$$0 \leq x_{pw} \leq 1.$$



Cost function

- **Increasing** and **Convex**
- Approximated by a **piecewise linear function** with **integer break points**
- Tight (close) to convex hull formulation
- Simplex finds integer optimal solution with high probability

A. Ozdaglar, D. Bertsekas, Transactions on Networking, 2003

Physical layer impairments

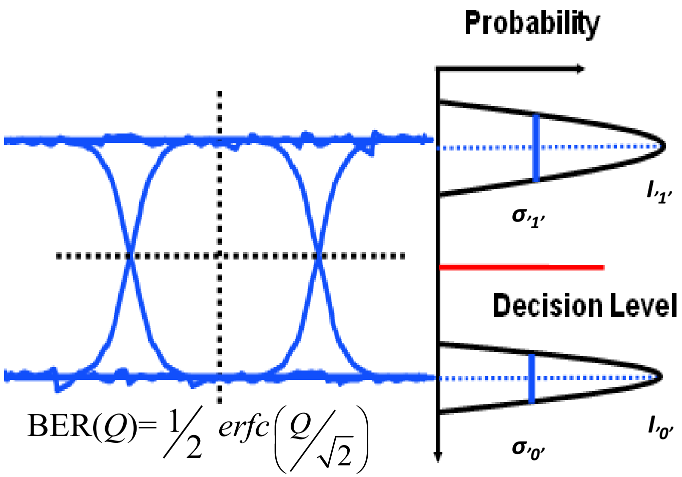
- Use impairment analytical models from literature
  - On-Off keying – 10 Gbps
  - Inter-lightpath: ASE, PMD, CD, SPM
  - Interference: intra-and inter-channel XT, XPM, FWM
- Quality of Transmission criterion: Q-factor (~ BER)

$$Q_p(w) = \frac{I_{'1',p}(w) - I_{'0',p}(w)}{\sigma_{'1',p}(w) + \sigma_{'0',p}(w)}$$

- Lightpath acceptable: $Q_p(w)$ < 15.5 dB

Eye diagram

(ON-OFF keying 10Gbps)



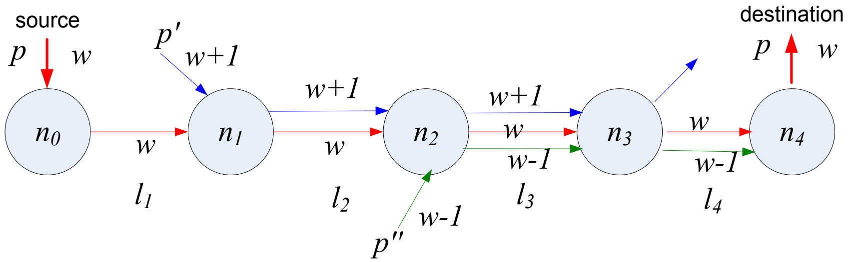
Modeling physical layer constraints in RWA

- From $Q_p(w)$ < 15.5 dB, find for each lightpath a bound on the acceptable noise variance of *interference* impairments

$$\sigma^2_{XT,'1',p}(w) + \sigma^2_{XPM,'1',p}(w) \le \sigma^2_{\max,p}(w)$$

- Express interference noise variance with lightpath utilization variables (x_{pw})
- Add in our LP formulation a constraint for each lightpath

Adjacent channel interference



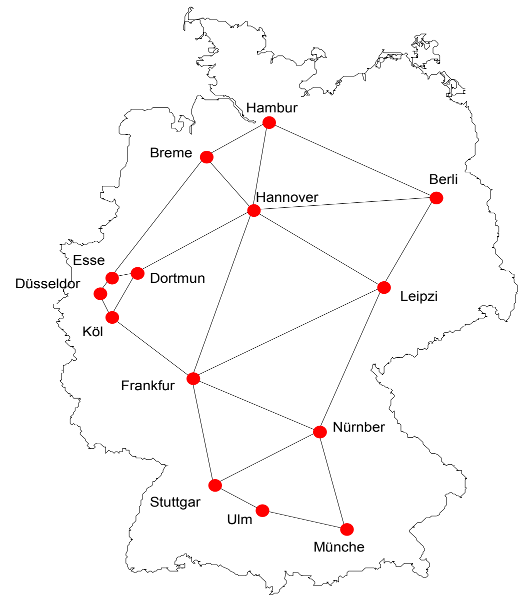
$$\sum_{\{l \in p | n \text{ end of } l\}} \left(\overbrace{s^2_{XT,n} \cdot \left(\sum_{\{p' | n \in p'\}} x_{p',w} \right)}^{\text{intra-XT}} + \overbrace{s^2_{XPM,l} \cdot \left(\sum_{\{p' | l \in p'\}} x_{p',w-1} + x_{p',w+1} \right)}^{\text{XPM from adjacent channels}} + \overbrace{s^2_{2-XPM,l} \cdot \left(\sum_{\{p' | l \in p'\}} x_{p',w-2} + x_{p',w+2} \right)}^{\text{XPM from second adjacent channels}} \right) + B \cdot x_{pw} - S_p \le \sigma^2_{\max,p}(w) + B$$

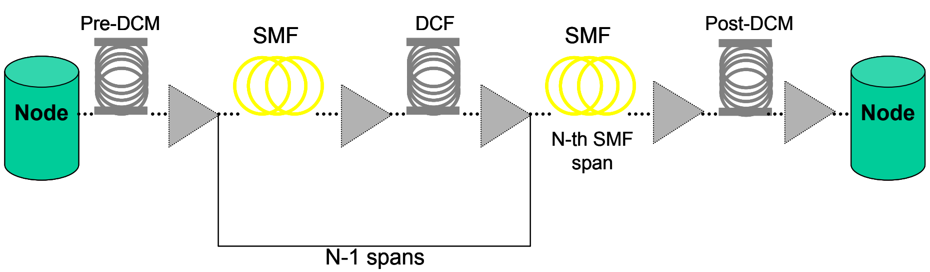
Solution: lightpaths that have acceptable interference → acceptable Q

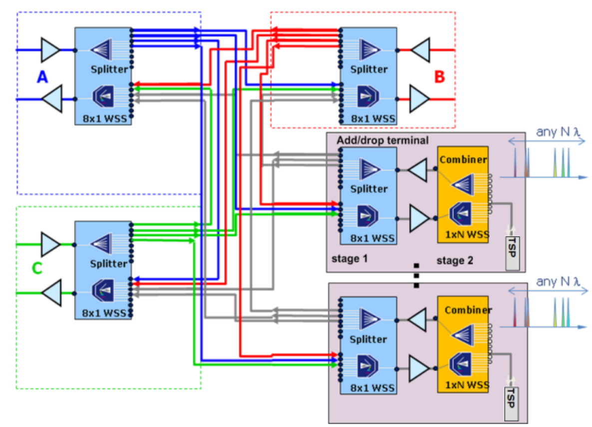
K. Christodoulopoulos, K. Manousakis, E. Varvarigos, IEEE/ACM Transactions on Networking, 2010

Performance evaluation results

- DT network topology
- DT actual traffic matrix of 2009 (scaled to capture future traffic)
- Realistic Link and node-OXC models
- Realistic physical layer parameters

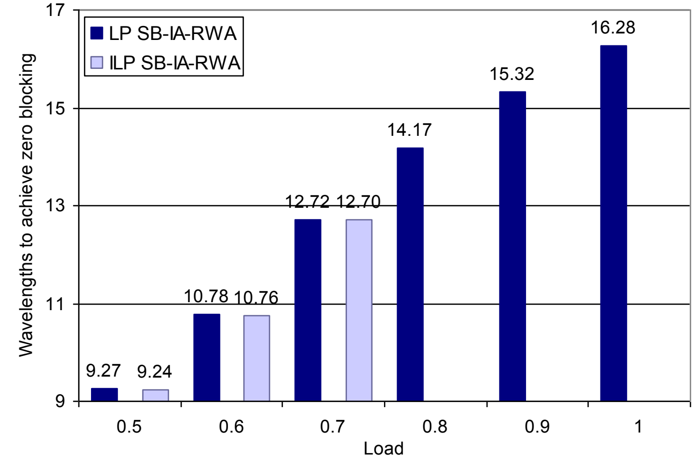


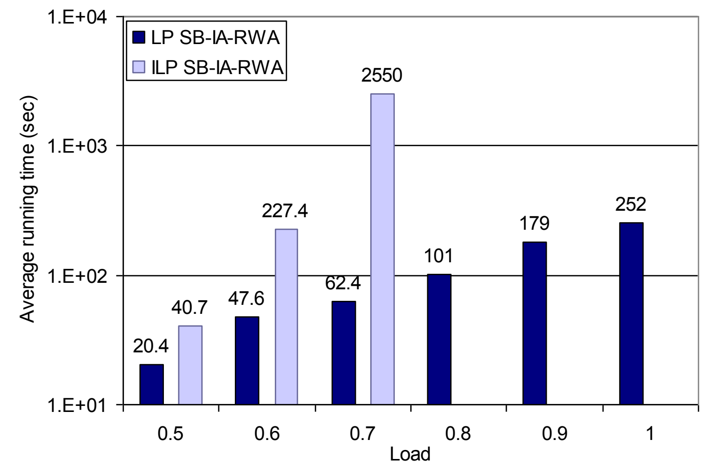




IA-RWA algorithm performance (optimality)

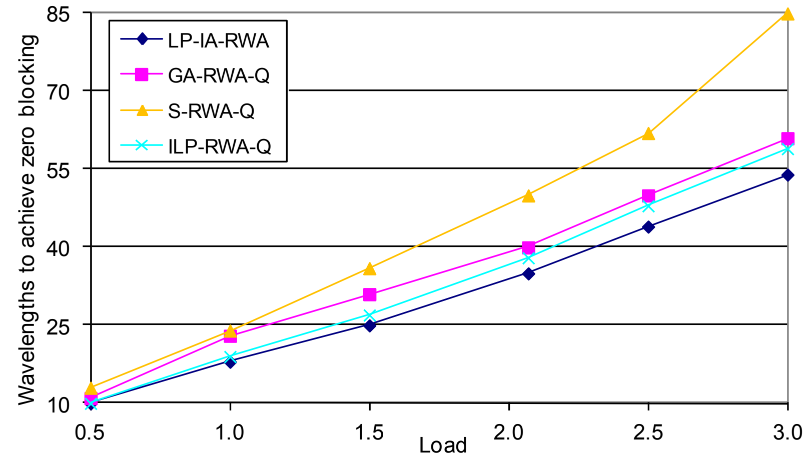
- Problem instances solved using
  - The proposed LP-relaxation algo
  - ILP
- 100 random traffic instances
- Zero blocking solutions
- Using ILP we were able to solve all instances within 5 hours up to load ρ=0.7
- LP-relaxation: the optimality is lost in 2-3 cases but the execution time is maintained low

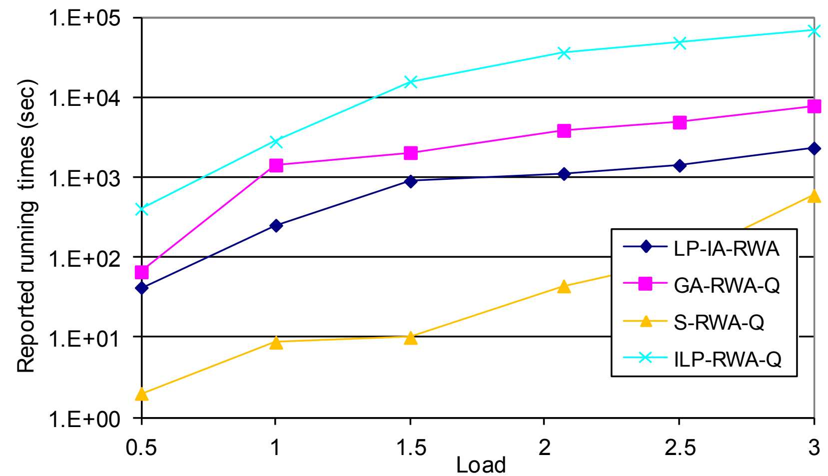




IA-RWA algorithms comparison

- Compare proposed algorithm (LP-IA-RWA) with algos by other researchers
  - GA-RWA-Q: genetic algorithm, separate PLI – Q verification module
  - S-RWA-Q : one-by-one sequential heuristic, separate PLI – Q verification module
  - ILP-WA-LU: ILP, PLIs taken indirectly into account
- LP-IA-RWA algorithm exhibits
  - best wavelength utilization performance
  - the second lower average running time





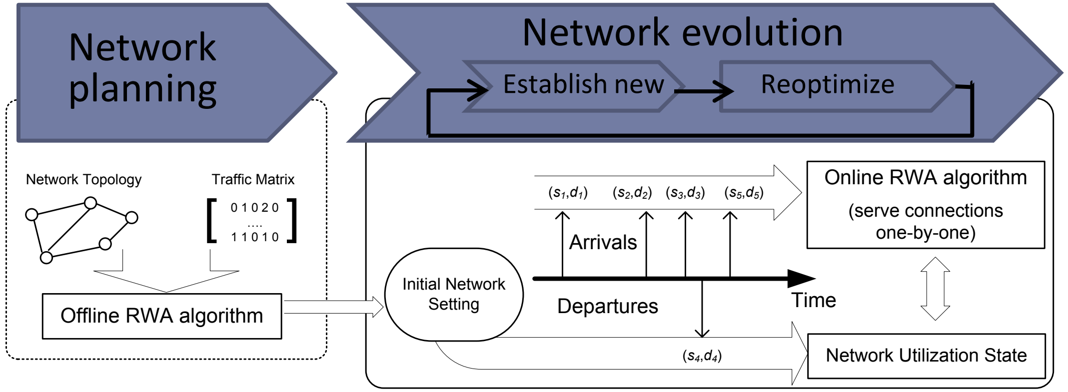
DICONET Deliverable D3.1

WDM network evolution

- As the network evolves, established connections are teared-down and new are established
- Operational phase
  - Establish new connection one-by-one (or a small set)

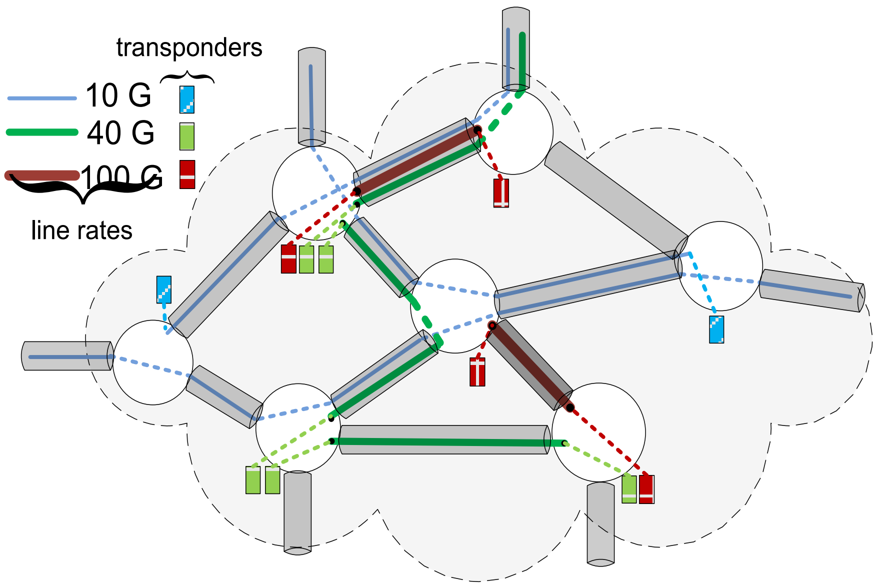
    Penalize re-routing of established lightpaths

    $$\text{minize } f(x_{pw}) + \gamma \cdot \sum_p \sum_w (x_{pw} - \bar{x}_{pw}),\ \bar{x}_{pw} \text{ previous solution, } f(x_{pw}) \text{ optimization objective}$$
  - Re-plan (re-optimize) the network
    - Periodically or On-demand



Mixed-line-rate (MLR)networks

- Network with more than one rate (various types of TxRx)
- Higher rate TxRx, more expensive, less reach
- Exploit the heterogeneity
  Serve distant connections with inexpensive, low-rate/long-reach TxRx, and short-distance high-rate connections with more expensive but fewer, high-rate TxRx



- Use advanced RWA algos to account for the different types of TxRx with different capabilities and costs
  - More complicated PLIs: cross-rate interference effects

Outline

- Generic optimization methods
  - Linear Programming, Integer Linear Programming
  - Meta-heuristics
  - Heuristics
- Standard WDM networks
  - Planning
  - Physical layer impairments
  - Network evolution
- Flexgrid optical networks
  - Planning
  - Physical layer impairments
  - Network evolution

Are standard WDM networks sufficient for future?

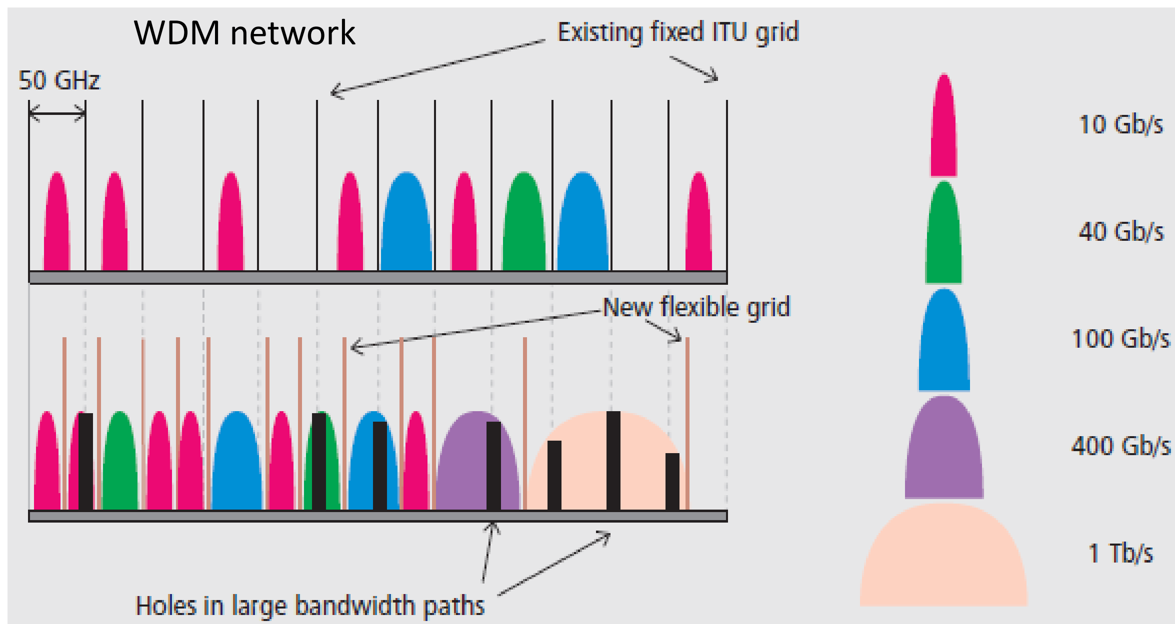
- WDM networks
  - To support increased capacity demands: 10Gbps → 40 and 100 Gbps
  - ITU fixed spectrum grid: all connections get 50 GHz (wavelength)
  - ☒ Inefficient use of resources
  - Desired system: *fine-granular*, *flexible*

☑ **Flexgrid** optical networks

- 6.25 or 12.5 GHz slots
- Slot coupling capabilities

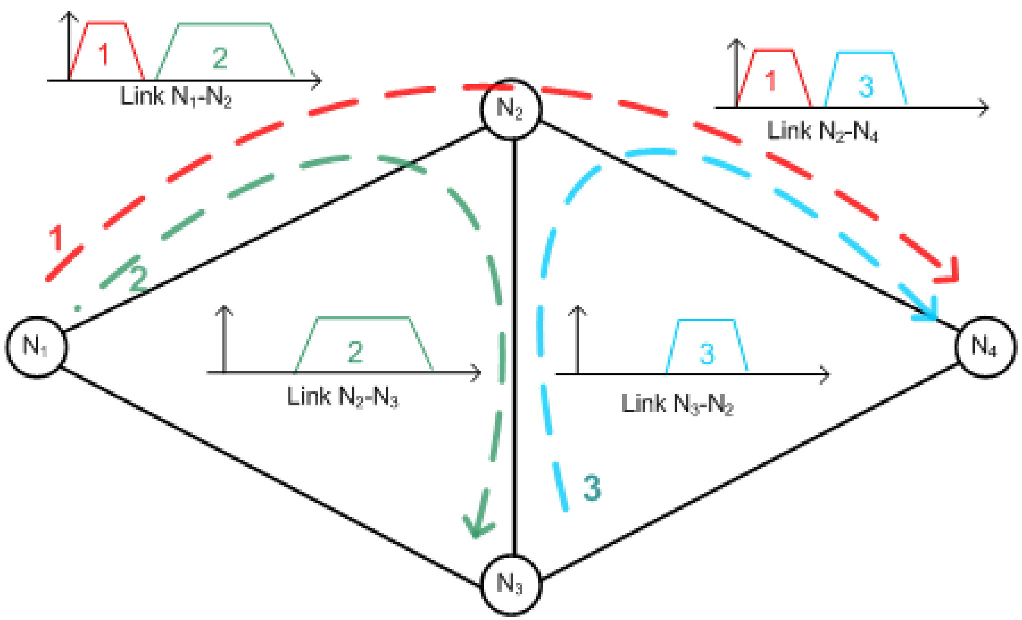
FP7 IP project

idealist



Flexgrid optical network

- Spectrum variable (non-constant) connections, in contrast to standard WDM
- Prototypes reported
  - Spectrum flexible OXCs
  - Spectrum flexible transponders
- 2 flexibility degrees: modulation level and spectrum used



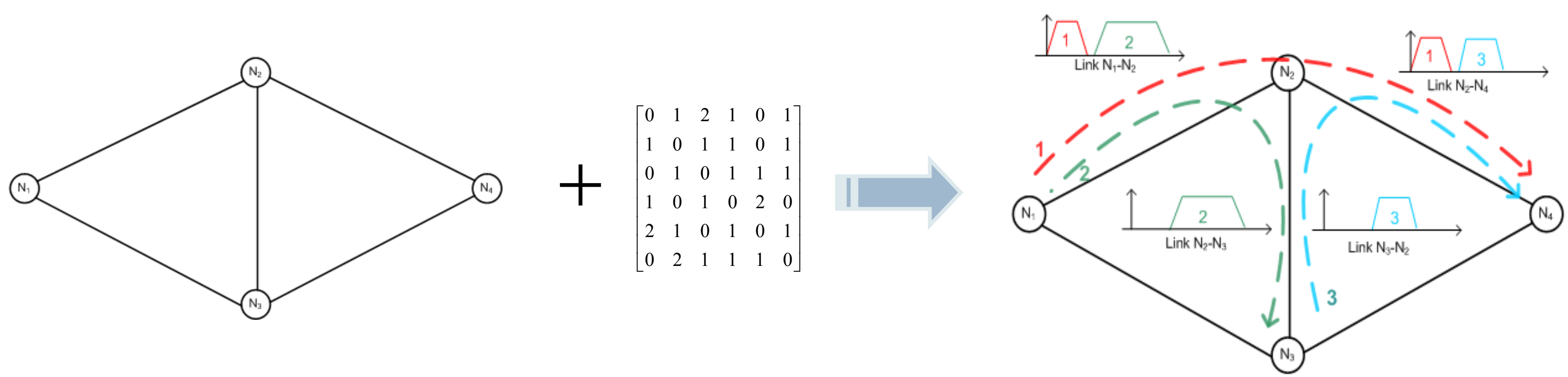
Benefits

☑ Finer granularity, spectrum savings, higher spectral efficiency

☑ Enable dynamic spectrum sharing: statistical multiplexing gains

Planning flexgrid networks

- Input: Network topology, traffic matrix, physical layer models
  - Proposed approach: describe TxRx feasible configurations with (reach-rate-spectrum-guardband-cost) tuples
- Output: Routes and spectrum allocation RSA (and also the modulation-level used - RMLSA)
  - Minimize utilized spectrum and/or number of transponders, and/or…
  - Satisfy physical layer constraints



Flexgrid TxRx and PLIs

- Flexgrid TxRx: tunable in spectrum and modulation level
- Describe flexgird TxRx feasible configurations with (reach-rate-spectrum-guardband-cost) tuples
  - Account for physical layer impairments
  - Account for spectrum- and modulation-format adaptation
  - Enable constant and non-constant guardband connections
  - Enable the use of multi-type TxRx with different capabilities
  - Can be also used for single- and mixed-line-rate WDM (fixed-grid) networks !!

    Need to translate the WDM (fixed-grid) TxRx specs to the specific input

    e.g. A 10,40,100Gbps MLR network with reaches 3200,2300 and 1500 km and relative costs1, 2.5 and 5, respectively, can be described with the following tuples:
    (10 Gbps-3200 km,50 GHz,0,1), (40 Gbps-2300 km,50 GHz,0,2.5), (100 Gbps-1500 km,50 GHz,0,5)

RSA vs. RWA

- Flexgrid networks have more flexibility degrees
  - Modulation level
  - # or allocated spectrum slots
- New formulations are required
  - Link & path formulations (as in RWA)
  - Spectrum slot allocation
    1. Slot-related variables: need constraints to allocate contiguous slots + discrete slot-assignment constraints (similar to RWA)
    2. Super-slot (set of contiguous slots) variables: need discrete super-slot assignment constraints
    3. Starting slot variables: need spectrum-ordering of demands to avoid slot overlapping
  - #spectrum slots > # wavelengths (could be >>)

  Formulations 1 and 2 that depend on the #slots might scale badly

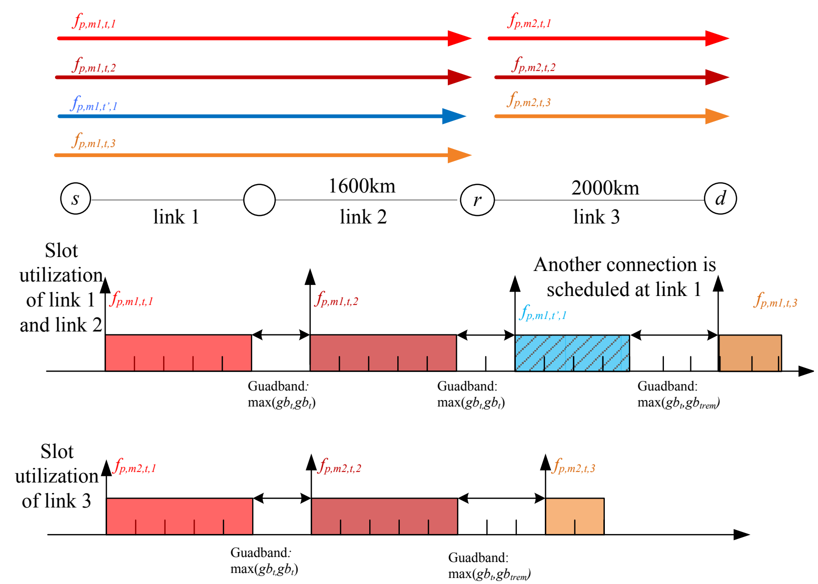
RSA algorithm example

- RSA algorithm example
  - Places regenerators (translucent network)
  - Decides how to break in more than one connections (if capacity demand at required distance> TxRx capabilities)
  - Multi-objective optimization: minimize cost and spectrum utilization Scalarization : a weighted combination of the 2 metrics

    (*w* · cost) + [(1- w) ·spectrum_slots]
- ILP formulation
  - Path formulation, based on starting slot variables

Demand (s,d): 50Gbps

Breaks in three (3) *translucent* connections over path p: two using t=[r_t=20,l_t=3700, b_t=5, g_t=2] and one using t_{rem}=[10, 3700, 3, 3]
Regeneration is used at intermediate node, so we have in total six (6) transparent connections, and m_1 and m_2 are the two sub-paths of p



K. Christodoulopoulos, P. Soumplis, E. Varvarigos, “Planning Flexgrid Optical Networks under Physical Layer Constraints”, submitted to JLT

RSA ILP algorithm

- Pre-processing phase
  - Given: Network graph, feasible (*rate-reach-spectrum-guardband-cost*) transmission configuration tuples of the TxRx
  - Calculate for each demand, a set of *k*-shortest paths
  - Identify the configurations (tuples) that can be used by the transponders over a path → define (path-tuple) pairs and calculate the #TxRx, #Reg, #spectrum slots required by each (path-tuple) pair
  - A (path-tuple) pair is a candidate solution to serve a demand
- RSA ILP algorithm selects the (path-tuple) pair to serve each demand and allocates spectrum slots
- Also developed a heuristic that serves demands one-by-one in some particular ordering (highest demand first), and uses simulated annealing to search among different orderings

ILP formulation

Inputs:

Λ	Traffic matrix that includes the requested demands, where Λ_{sd} corresponds to the demand (s,d)
P_{sd}	Set of alternative paths for demand (s,d)
Q_{sd}	Set of non-dominated path-tuple pairs for demand (s,d) assuming a translucent network setting
$C_{p,t}$	Cost of transponders required to serve demand (s,d) using path $p\in P_{sd}$ and tuple $t\in T$, that is, using path-tuple pair (p,t)
$W_{p,t}$	Number of connections required to serve demand (s,d) using path $p\in P_{sd}$ and tuple $t\in T$, that is, using path-tuple pair (p,t)
$b_{p,t,i}$	Number of spectrum slots required for data transmission without guardband for flexgrid lightpath (p,t,i) [lightpath $i\in\{1,2,\ldots,W_{p,t}\}$ of path-tuple pair (p,t)]. In particular, if $W_{p,t}=1$ then $b_{p,t,i}=b_t$, and if $W_{p,t}>1$ then $b_{p,t,i}=b_t$ for $i\in\{1,2,\ldots,W_{p,t}-1\}$ and $b_{p,t,i}=b_{t_{rem}}$ for $i=W_{p,t}$.
$g_{p,t,i}$:	Number of guardband spectrum slots required for the data transmission for flexgrid lightpath (p,t,i). In particular, if $W_{p,t}=1$ then $g_{p,t,i}=g_t$, and if $W_{p,t}>1$ then $g_{p,t,i}=g_t$ for $i\in\{1,2,\ldots,W_{p,t}-1\}$ and $b_{p,t,i}=g_{t_{rem}}$ for $i=W_{p,t}$.
F_{total}	Upper bound on the number of spectrum slots required for serving all connections set to $F_{TOTAL}=\sum_{sd}\max_{(p,t)\in Q_{sd}}\left(S_{p,t}\right)$
W	Objective weighting coefficient, taking values between 0 and 1. Setting $w=0$ (or $w=1$) minimizes solely the cost of transponders used (or the total spectrum used, respectively).

Variables:

$x_{p,t}$	Boolean variable, equal to 1 if path-tuple pair $(p,t)\in Q_{sd}$ is used to serve demand (s,d) and equal to 0 otherwise.
$f_{p,m,t,i}$	Integer variable that denotes the starting spectrum slot for flexgrid transparent lightpath (p,m,t,i) [lightpath over sub-path $m\in R_{p,t}$ of translucent connection $i\in\{1,2,\ldots,W_{p,t}\}$ of path-tuple pair (p,t)]. If path-tuple pair (p,t) is not utilized to serve (s,d) then variable $f_{p,m,t,i}$ is free and does not play a role in the solution. Note that $f_{p,m,t,i}<F_{total}$.
$\delta_{p,m,t,i,p',m',t',i'}$	Boolean variable that equals 0 if the starting frequency $f_{p,m,t,i}$ for flexgrid transparent lightpath (p,m,t,i) is smaller than the starting frequency $f_{p',m',t',i'}$ for flexgrid lightpath (p',m',t',i'), i.e., $f_{p,m,t,i}<f_{p',m',t',i'}$. Variable $\delta_{p,m,t,i,p',m',t',i'}$ is defined only if sub-paths $m\in R_{p,t}$ and $m'\in R_{p',t'}$ share a common link.
S	Highest spectrum slot used.
C	Cost of utilized transponders.

minimize $w\cdot S+(1-w)\cdot C$

- *Cost function definition:*

For all (s,d) pairs, all $(p,t)\in Q_{sd}$, all $i\in\{1,2,\ldots,W_{p,t}\}$, and all $m\in R_{p,t}$,

$$S\geq f_{p,m,t,i}+b_{p,t,i}.$$

$$C=\sum_{sd}\sum_{(p,t)\in Q_{sd}}C_{p,t}\cdot x_{p,t}.$$

- *Path-tuple pair selection:*

For all (s,d) pairs, $\sum_{(p,t)\in Q_{sd}}x_{p,t}=1$.

- *Starting frequencies ordering constraints:*

For all (s,d) pairs, all $(p,t)\in Q_{sd}$, all $m\in R_{p,t}$, all $i\in\{1,2,\ldots,W_{p,t}\}$, all (s',d'), all $(p',t')\in Q_{s'd'}$, all $m'\in R_{p',t'}$ where m and m' share at least one common link, and all $i'\in\{1,2,\ldots,W_{p',t'}\}$,

$$\delta_{p,m,t,i,p',m',t',i'}+\delta_{p',m',t',i',p,m,t,i}=1,$$

$$f_{p',m',t',i'}-f_{p,m,t,i}\leq F_{total}\cdot\delta_{p,m,t,i,p',m',t',i'},$$

$$f_{p,m,t,i}-f_{p',m',t',i'}\leq F_{total}\cdot\delta_{p',m',t',i',p,m,t,i}.$$

- *Non-overlapping spectrum constraints:*

For all (s,d) pairs, all $(p,t)\in Q_{sd}$, all $m\in R_{p,t}$, all $i\in\{1,2,\ldots,W_{p,t}\}$, all (s',d'), all $(p',t')\in Q_{s'd'}$ all $m'\in R_{p',t'}$ where m and m' share at least one common link, and all $i'\in\{1,2,\ldots,W_{p',t'}\}$

$$f_{p,m,t,i}-\left(b_{p,t,i}+\max\left(g_{p,t,i},g_{p',t',i'}\right)\right)-f_{p',m',t',i'}\leq$$
$$\left(F_{total}+\max\left(g_{p,t,i},g_{p',t',i'}\right)\right)\cdot(1-\delta_{p,m,t,i,p',m',t',i'}+2-x_{p,t}-x_{p',t'})$$

$$f_{p',m',t',i'}-\left(b_{p',t',i'}+\max\left(g_{p,t,i},g_{p',t',i'}\right)\right)-f_{p,m,t,i}\leq$$
$$\left(F_{total}+\max\left(g_{p,t,i},g_{p',t',i'}\right)\right)\cdot(1-\delta_{p',m',t',i',p,m,t,i}+2-x_{p',t'}-x_{p,t})$$

RSA vs. MLR

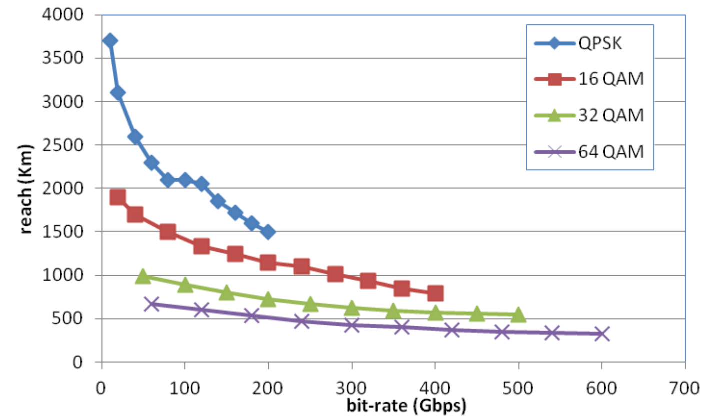
TxRx capabilities according to (*)

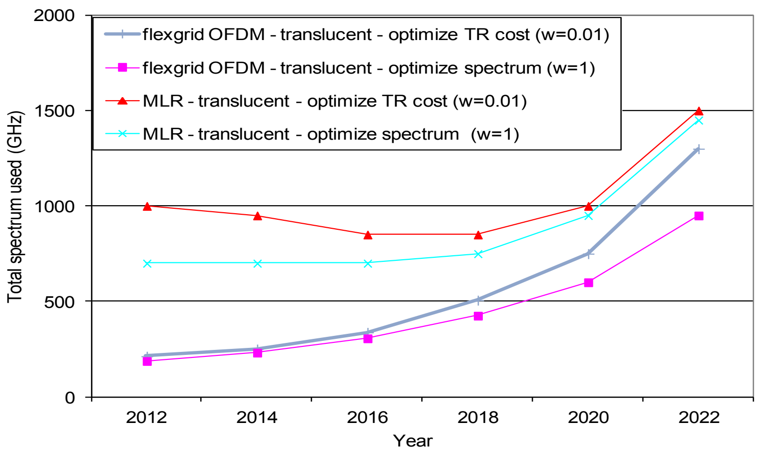
Flexgrid vs. MLR network

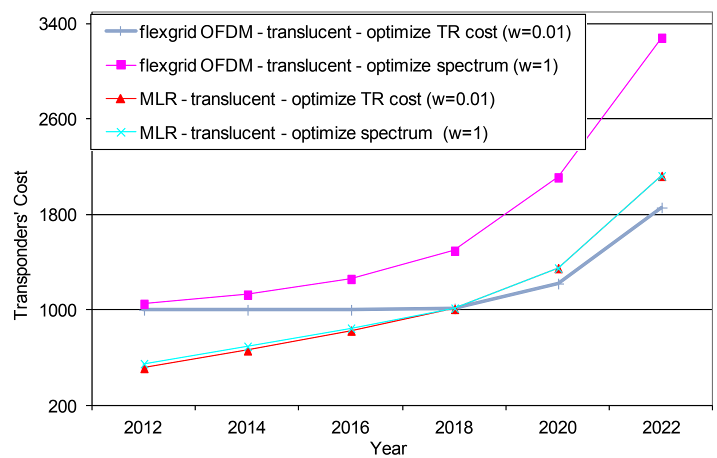
(assuming similar reach-rate capabilities)

2 optimization options: optimize spectrum (*w*=1) or cost (*w*=0.01)

Reach vs rate capabilities of the flexgrid TxRx



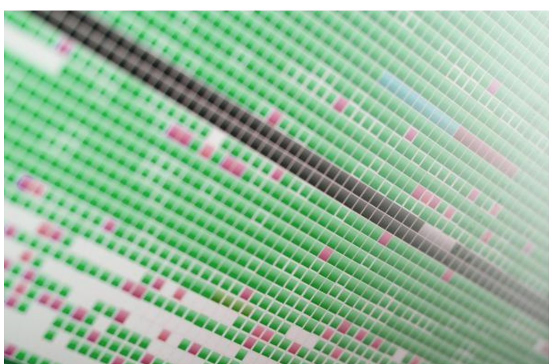




* A. Klekamp, R. Dischler, R. Buchali, "Limits of Spectral Efficiency and Transmission Reach of Optical-OFDM Superchannels for Adaptive Networks", IEEE Photonics Technology Letters, 23(20), 2011.

Flexgrid network evolution

- Flexgrid: finer granularity and more flexibility (when compared to WDM that have wavelength-level granularity, non-tunable transmissions)
- Flexgrid network evolution differs from WDM
  - Traffic variation can be accommodated at different levels
    - new connection requests
    - traffic variation of established connections, served by tuning the TxRx
  - Re-optimization: spectrum fragmentation (more severe in flexgrid)

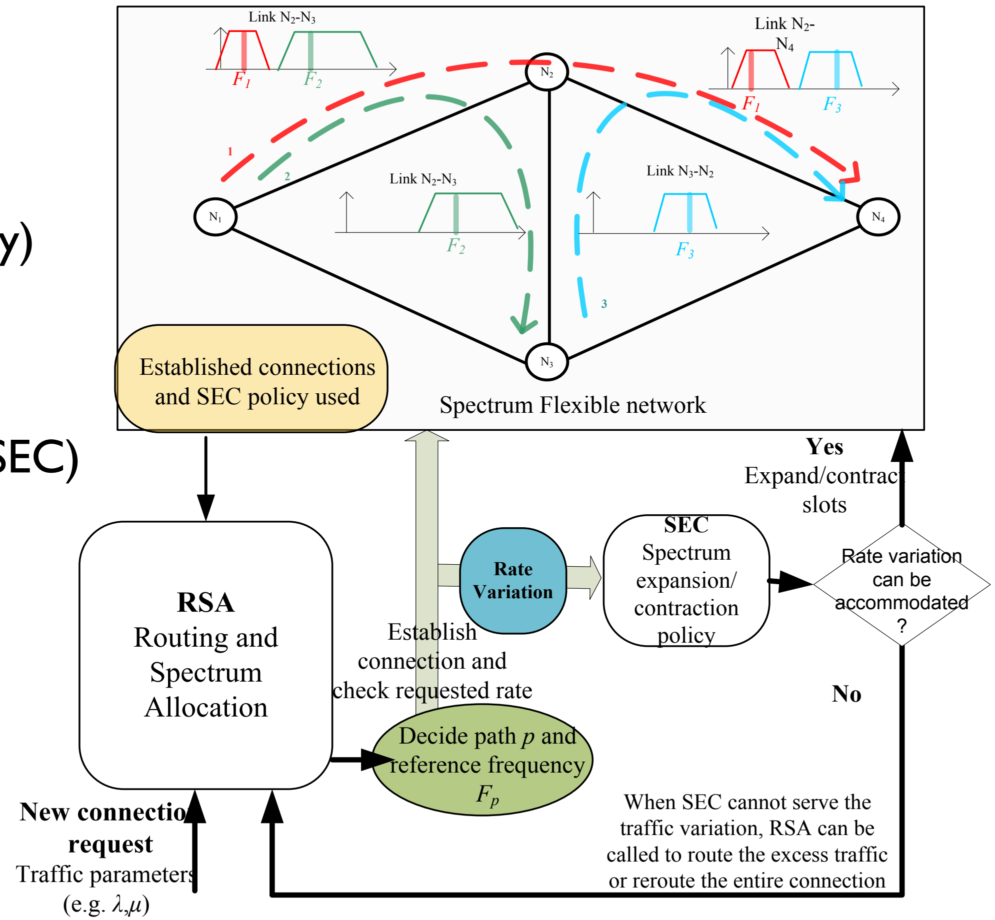


Hard disc defragmentation

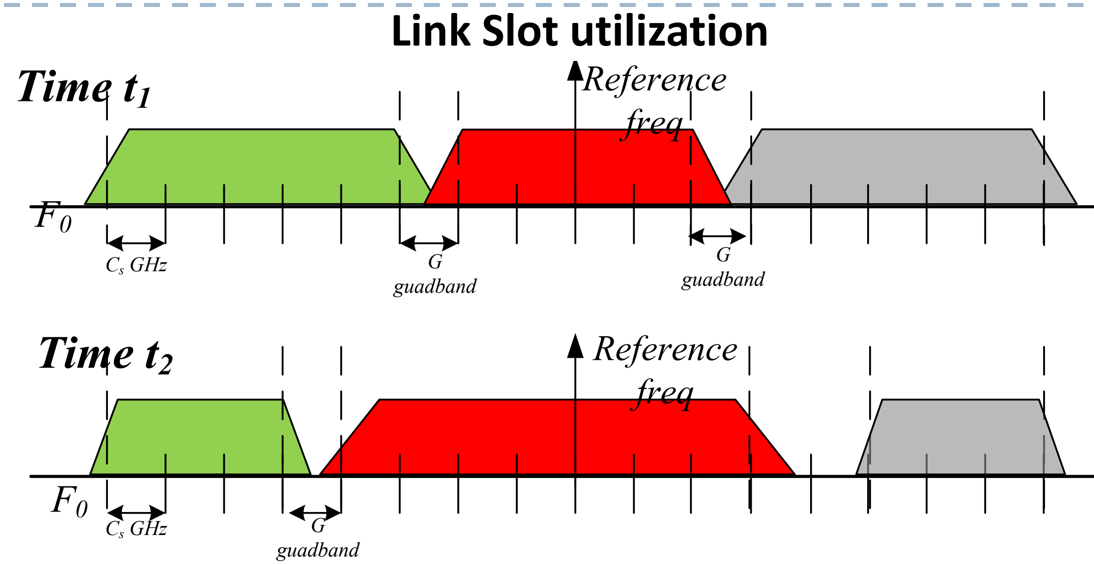
Flexgrid network evolution

Traffic variations can be accommodated at different levels

- **1st level**: New connection request
  - RSA algo serves the request (assign path and reference frequency)
- **2nd level**: traffic variation of existing connection
  - Spectrum Expansion/Contraction (SEC)
  - If the SEC fails (cannot find free additional slots) → trigger RSA to setup an additional connection or reroute the existing



Dynamic spectrum sharing



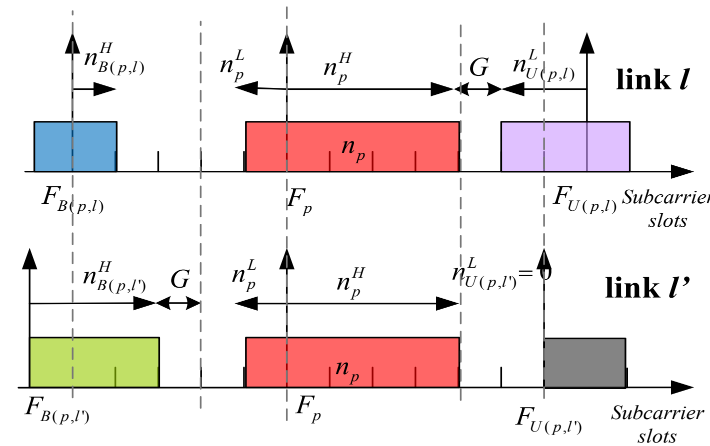
- Slotted spectrum (e.g. 6.25 GHz)
- *G* Guardband slot(s) is (are) required between connections

- A connection
  - is assigned a path and a reference frequency
  - utilizes slots around reference frequency
  - *expands* / *contracts* its spectrum to follow the traffic variations
- A slot is assigned to only one connection at a given time instant
- Slots are shared among connections at different time instants

Spectrum Expansion/Contraction (*SEC*) policy

SEC policies and dynamic RSA algorithm

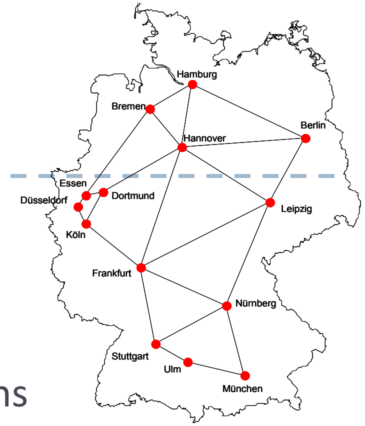
- SEC policy examples
  - CSA policy
    - Connection exclusively uses a set of slots
    - No spectrum sharing
  - DHL policy
    - Expansion: use higher spectrum slots, until find a used slot, then use lower spectrum slots, opposite when contract
    - Dynamic spectrum sharing
  - Analytical models to calculate network blocking



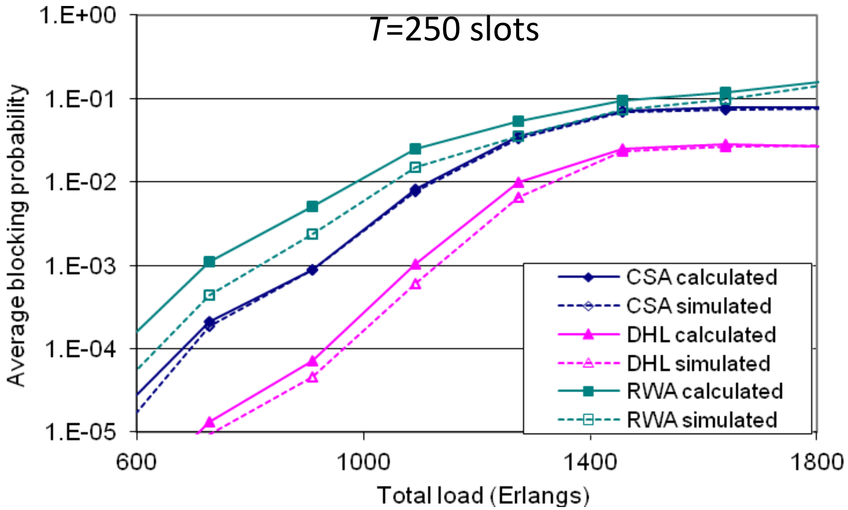
- RSA algorithm for serving time-varying traffic
  - Allocates route and reference frequency
  - Takes into account the SEC policy used (through the analytical model) to calculate the total average network blocking probability

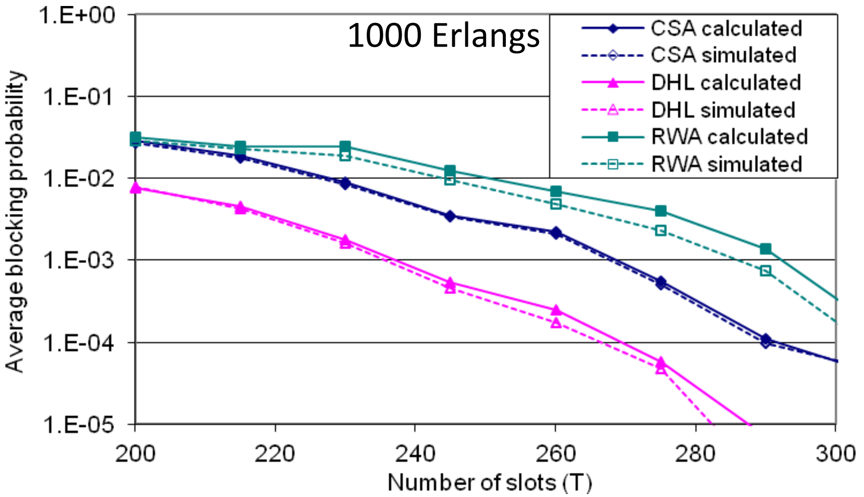
K. Christodoulopoulos, I. Tomkos, E. Varvarigos, “Time-Varying Spectrum Allocation Policies in Flexible Optical Networks”, IEEE JSAC, 2013

Performance results



- Traffic: Single connection between every pair of nodes
  - Each connection generates slots according to a birth-death process
- Network supports *T* slots, Guardband *G*=1 slot
- Compare Spectrum Flexible network to a WDM system with T/2 wavelengths





- Spectrum flexible network exhibits superior performance (DHL is up to 2 orders of magnitude better than WDM-RWA case)
- Dynamic spectrum sharing (DHL policy) reduces the blocking compared to constant spectrum allocation (CSA policy)
- The proposed analytical models are in close agreement with the corresponding simulations

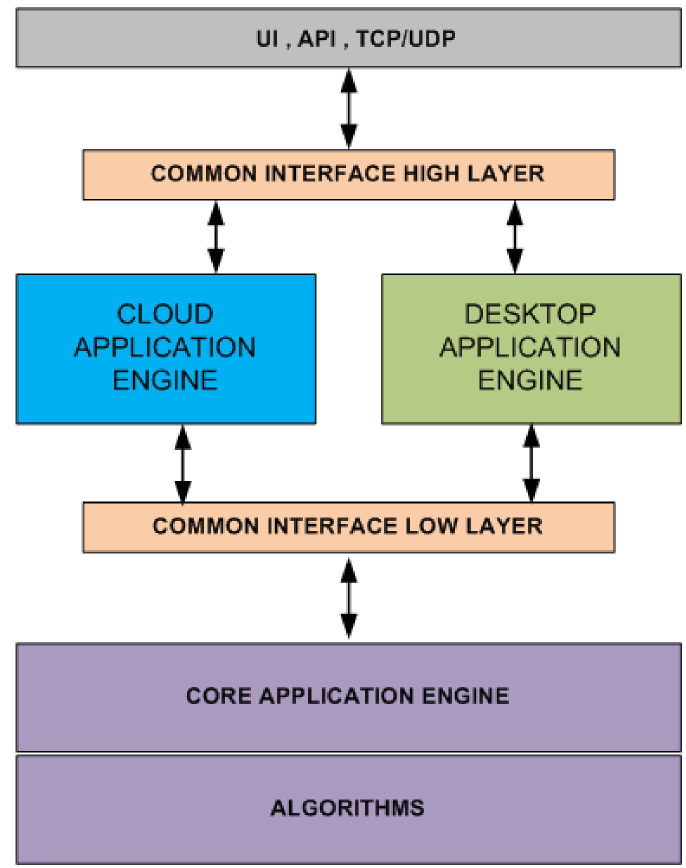
Network Planning and Operation Tool

- Consolidate planning and operation algorithms in a software tool: *Network Planning and Operation Tool* (NPOT)
- Useful for *network operators*, *equipment vendors* and *researchers*

  Can be used to investigate several issues :
  - the choice of the optical technology to be used
  - the topology design
  - the placement of optical equipment (e.g., transponders, regenerators, etc) at the various nodes
  - the offline or online routing and wavelength (or spectrum) assignment for the connection requests
  - account for physical-layer impairments

MANTIS – Upatras NPOT

- MANTIS developed at University of Patras
  - Service (cloud)
  - Desktop application
- Current MANTIS state
  - Web-page UI
  - Desktop application engine
  - Core application engine
  - Offline RSA algorithm
    - Heuristic and ILP (using CPLEX)
- Goal: Mantis to be a reference to compare network architectures and algorithms



Summary

- General methods to solve optimization problems in networks
- WDM networks
  - Goal of planning: satisfy traffic and optimize resource usage
  - Physical layer impairments (cross-layer optimization)
  - Network evolution: establish new connections and re-optimize
- Flexgrid networks
  - Added complexity due to more flexibility degrees

    Interdependence among reach-rate-spectrum-guardband parameters

    Traffic variation can be accommodated at different levels
  - Develop novel formulations
- Network Planning and Operation Tools - Mantis

Thank you for your attention!

Questions ?

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