Design and Re-optimization Algorithms for Elastic Optical Networks

Luis Velasco
lvelasco@ac.upc.edu
I. RSA Basics
II. Network Design
III. RSA under Dynamic Traffic
IV. Extending networks life-cycle
V. Towards Cognitive Networking
Part I
RSA basics

Luis Velasco
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 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.
INPUT S, d  
OUTPUT C(d) 

1: Initialize: C(d) ← 0_{|S|-n_d+1 x |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 set 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 \( d \).

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.

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

subject to:

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

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

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

\[
\begin{align*}
(NL - CA) \quad \text{min} & \quad \sum_{e \in E} z_e \\
\text{subject to:} & \\
\sum_{e \in E(v)} \sum_{c \in C(d)} w_{dec} &= 1 \quad \forall d \in D, v \in \{s_d, t_d\} \\
\sum_{e \in E(v)} \sum_{c \in C(d)} w_{dec} &\leq 2 \quad \forall d \in D, v \in \{s_d, t_d\} \\
\sum_{e' \in E(v)} \sum_{c' \in C(d')} w_{dec} &\geq w_{dec} \quad \forall d \in D, c \in C(d'), v \in \{s_d, t_d\}, e \in E(v) \\
\sum_{d \in D} \sum_{c \in C(d)} \gamma_{cs} \cdot w_{dec} &\leq 1 \quad \forall e \in E, s \in S \\
\sum_{d \in D} \sum_{c \in C(d)} w_{dec} &\leq |S| \cdot z_e \quad \forall e \in E
\end{align*}
\]

\( \mathcal{O}(\mathcal{D} \cdot \mathcal{E} \cdot \mathcal{C}) \) variables

\( \mathcal{O}(\mathcal{D} \cdot \mathcal{C} \cdot \mathcal{N} \cdot \mathcal{E}) \) constraints

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.
Part II
Network Design

Luis Velasco
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.
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.

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:
  \[
  \sum_{a \in A} \sum_{a' \in A, a' \neq a} \frac{b_{aa'}}{\Delta f \cdot B_{mod}} \leq \sum_{a \in A} \sum_{a' \in A, a' \neq a} \frac{b_{aa'}}{\Delta f' \cdot B_{mod}}
  \]

- 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**.

**Metro Area Partitioning**
- Set of locations
- Potential metros
- Traffic matrix
- Slice width

**Network Design**
- 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 ($\Delta f$) 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.

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.
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

<table>
<thead>
<tr>
<th>Year A</th>
<th>Four different destinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gb/s</td>
<td>Y1</td>
</tr>
<tr>
<td>&lt;=100</td>
<td>85.7%</td>
</tr>
<tr>
<td>(100-200]</td>
<td>14.3%</td>
</tr>
<tr>
<td>(200-300]</td>
<td>0.0%</td>
</tr>
<tr>
<td>(300-400]</td>
<td>0.0%</td>
</tr>
<tr>
<td>&gt;400</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year B</th>
<th>Two different destinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gb/s</td>
<td>Y1</td>
</tr>
<tr>
<td>150 Gb/s</td>
<td>150 Gb/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year C</th>
<th>One single destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gb/s</td>
<td>Y1</td>
</tr>
<tr>
<td>400 Gb/s</td>
<td>400 Gb/s</td>
</tr>
</tbody>
</table>

Transponder Type | Cost
---|---
1Tb/s SBVT | 5
400Gb/s SBVT | 3
400Gb/s FT | 2
100Gb/s FT | 1

Number of Transponders

Accumulated present cost
Migrating Towards Flexgrid Technology

1. Sub-network Upgrading
2. Enlarging the core
3. Extending the core towards the metro

Migrating connections

Fixed grid

Flexgrid

Mixed grid

Mixed grid

M2K.1 Luis Velasco
Migration flow chart

Network Reconfiguration

Requirements met?

yes

Network Upgrading

Creating/extending flexgrid islands

Enlarging to un-deployed areas

Extending to border metro areas

no

Planning requests

Planning Department

Planning requests

Planning Department

Reconfiguration requests

NMS

Inventory

Purchasing, Installing, Reconfiguring, Testing

Engineering Department

Network

Network Reconfiguration

yes

Requirements met?

Network Upgrading

Creating/extending flexgrid islands

Enlarging to un-deployed areas

Extending to border metro areas

no

Planning requests

Planning Department

Planning requests

Planning Department

Reconfiguration requests

NMS

Inventory

Purchasing, Installing, Reconfiguring, Testing

Engineering Department

Network

Network Reconfiguration

yes

Requirements met?

Network Upgrading

Creating/extending flexgrid islands

Enlarging to un-deployed areas

Extending to border metro areas

no

Planning requests

Planning Department

Planning requests

Planning Department

Reconfiguration requests

NMS

Inventory

Purchasing, Installing, Reconfiguring, Testing

Engineering Department
Part III
RSA under Dynamic Traffic

Luis Velasco
Source of traffic variations

Reducing aggregation level might increase traffic variations

Datacenter interconnection to transfer bulk data

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.

---

M2K.1

Luis Velasco

---

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

Start

Connection request $d$ arrives

Run RSA algorithm

Run Re-optimization algorithm

Solution found?

Solution found?

Establish path

End

Yes

No

Yes

No

Perform Re-optimization

Block connection request
Gains of Defragmentation

<table>
<thead>
<tr>
<th>Network</th>
<th>25 GHz</th>
<th>12.5 GHz</th>
<th>6.25 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEL</td>
<td>30.4%</td>
<td>28.4%</td>
<td>30.3%</td>
</tr>
<tr>
<td>BT</td>
<td>22.9%</td>
<td>23.0%</td>
<td>34.1%</td>
</tr>
<tr>
<td>DT</td>
<td>22.2%</td>
<td>24.8%</td>
<td>33.0%</td>
</tr>
</tbody>
</table>

Example of Re-optimisation (Elasticity)

Initial Spectrum

50 GHz  50 GHz  37.5 GHz

Spectrum Shifting

Elastic Operation

75 GHz
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.

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; $iv)$ a set of multicast demands to be served identified by the tuple $<s_d, T(d), b_d>$; $v)$ 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).

Multicast connections: Optical vs Multilayer

**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.

# Bitrate Squeezed and Multi-path Recovery

## Path Recovery and Description

<table>
<thead>
<tr>
<th>Path Recovery</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Protection</strong></td>
<td>Protection routes are known in advance:</td>
</tr>
<tr>
<td></td>
<td>• Dedicated Protection</td>
</tr>
<tr>
<td></td>
<td>• Shared Protection</td>
</tr>
<tr>
<td><strong>Restoration</strong></td>
<td>Restoration routes are found adaptively based on the failure and the state of the network at the time of failure.</td>
</tr>
</tbody>
</table>

### Diagrams

- **Working Path**: A path through the network that is currently in use.
- **Backup Paths**: Paths that are available in case of failure and are reserved.
- **Restoration Paths**: Paths that are activated when the working path fails.

After Failure Repair Re-optimization (AFRO)


Modulation Format-aware Restoration and Re-optimization

SBVTs under dynamic traffic

- Restoration

### Mod. Format

<table>
<thead>
<tr>
<th>Mod. Format</th>
<th>bits/symbol</th>
<th>Reach</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP-QPSK</td>
<td>4</td>
<td>3000 Km</td>
</tr>
<tr>
<td>DP-QAM8</td>
<td>6</td>
<td>1000 Km</td>
</tr>
<tr>
<td>DP-QAM16</td>
<td>8</td>
<td>650 Km</td>
</tr>
</tbody>
</table>

### Path Id | Bitrate (Gb/s) | Len. (Km) | Mod. Format | Slot Width |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>400</td>
<td>550</td>
<td>DP-QAM16</td>
<td>100 GHz</td>
</tr>
<tr>
<td>P1a</td>
<td>200</td>
<td>300</td>
<td>DP-QAM16</td>
<td>50 GHz</td>
</tr>
<tr>
<td>P1b</td>
<td>100</td>
<td>1250</td>
<td>DP-QPSK</td>
<td>50 GHz</td>
</tr>
</tbody>
</table>
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$_0^r$, s$_1^r$, t$_1^r$, 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$_0^r$), the scheduled slot allocation (s$_1^r$) to be performed at time $t^r_1$, 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$_0^r$) and the scheduled completion time ($t_r$) for the new transference request. The bitrate of the connection is given by $b(s_0^r, l(r_r))$, where $l(r_r)$ returns the total length of the route $r_r$.
- the new spectrum allocation ($w_0^r$), scheduled reallocation ($w_1^r$, $t_1^r$) 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.

Results

a) Unserved bitrate (%)

b) Transfer time (s)
CVN Provisioning with QoS Constraints and Bitrate Guarantees

QoS constraints

Bitrate guarantees

Maximum delay allowed between EPs

SRLG-disjoint MPLS paths

SRLG identifiers

Capacity matrix

Quality of Service (QoS)

Bitrate guarantees

*t_0*

*t_1*

*t_2*
Part IV
Extending networks life-cycle

Luis Velasco
Migration towards in-operation network planning

**Application-based Network Operations (ABNO)**

- **North Bound Interface**
  - ABNO Controller
  - TED
  - LSP-DB
  - VNTM
  - PCE
  - Prov. Mngr
  - OAM Handler

- **South Bound Interface**
  - Metro (Vendor A)
  - Metro (Vendor B)
  - IP/MPLS (Vendor A)
  - OXC (Vendor A)
  - IP/MPLS (Vendor B)
  - OXC (Vendor B)

**In-Operation Planning Tool**

- Internet
- Voice
- CDN
- Cloud
- Business

**GMPLS Control Plane**

- Metro OSS
- IP/MPLS Core OSS
- Optical Transport OSS

**Other**

- Metro
- OSS

---

M2K.1 Luis Velasco
Re-optimisation Process

In-operation Planning

New Services  Population Grow

Periodical

Forecast

Periodical Network Design

Monitor and Measure

Reconfigure / Re-optimise

Network Operation

In-operation planning

Operation
- Provisioning
- Recovery
Incremental Planning

![Diagram of network planning](image)
Results
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
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 lifecycle.
- Data analytics were introduced as a way to add cognition to the network.
Thank you for your attention!

Luis Velasco
lvelasco@ac.upc.edu

March, 2016