Master's degree in computer engineering and telematics
17th July 2018

Dimensioning and Optimization in Optical Transport Networks

Tiago Duarte Esteves

Supervisor: Prof. Armando Humberto Moreira Nolasco Pinto
Co-Supervisor: Dr. Rui Manuel Dias Morais

universidade de aveiro
instituto de telecomunicações
Coriant

CONTENTS

- Motivation
- Network specification
- Capital expenditures
- Integer linear programming
- Comparative analysis
- Conclusions

MOTIVATION

- The crucial premise for network operators to choose the technology and architecture to deploy is **cost minimization.**

- The **tools used** in transport network planning are the **integer linear programming models, heuristic algorithms** and **analytical calculations** for estimating results.

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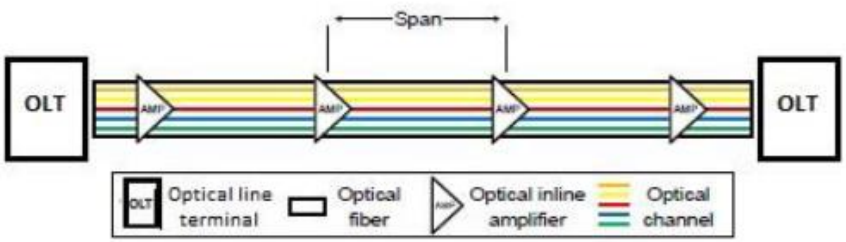
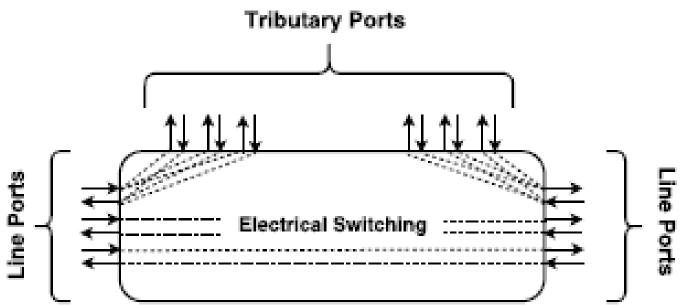
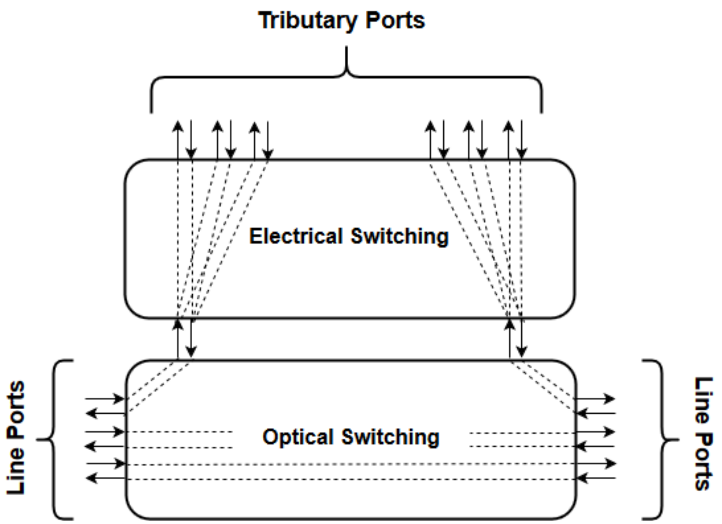
NETWORK COMPONENTS

Link architecture



Node architecture





The links are physical point-to-point connections ensured by the transmission systems between two adjacent nodes.

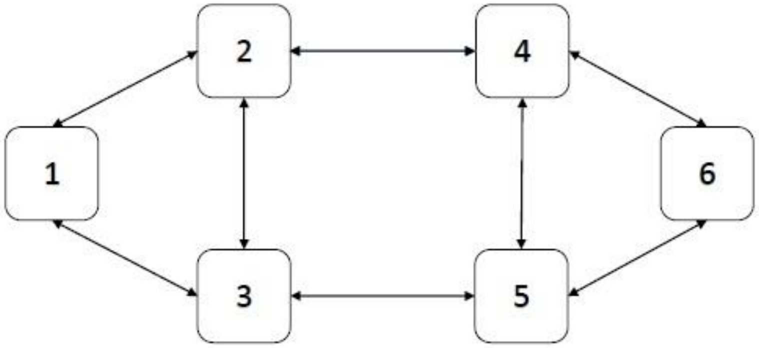
Each link has two optical line terminals, one at each end.

The signals are transmitted through a pair of fibers with bidirectional communication.

Contain optical amplifiers at an expected distance (span) to increase signal strength.

REFERENCE NETWORK

- In this specific case, the physical topology of the reference network consists of 6 nodes and 8 bidirectional links.
- The distance matrix for this reference network is the same regardless of the associated traffic.
- The values indicated in the matrix are expressed in kilometers (km) and this matrix is symmetric.



$$Dist = \begin{bmatrix} 0 & 460 & 663 & 0 & 0 & 0 \\ 460 & 0 & 75 & 684 & 0 & 0 \\ 663 & 75 & 0 & 0 & 890 & 0 \\ 0 & 684 & 0 & 0 & 103 & 764 \\ 0 & 0 & 890 & 103 & 0 & 361 \\ 0 & 0 & 0 & 764 & 361 & 0 \end{bmatrix}$$

TRAFFIC NETWORK

For this study three traffic scenarios for the reference network are created, being: **low traffic, medium traffic** and **high traffic**.

For each scenario different traffic matrices will be created where these matrices are represented taking into account the different bit rates ODU0, ODU1, ODU2, ODU3 and ODU4.

In each scenario it has a total bidirectional traffic, which is:

- Low traffic scenario – **0,5 Tbits/s**
- Medium traffic scenario – **5 Tbits/s**
- High traffic scenario – **10 Tbits/s**

LOW TRAFFIC – 0,5 TBITS/S

$$ODU0 = \begin{bmatrix} 0 & 5 & 1 & 3 & 1 & 3 \\ 5 & 0 & 0 & 1 & 5 & 0 \\ 1 & 0 & 0 & 1 & 4 & 1 \\ 3 & 1 & 1 & 0 & 1 & 1 \\ 1 & 5 & 4 & 1 & 0 & 3 \\ 3 & 0 & 1 & 1 & 3 & 0 \end{bmatrix} \quad ODU1 = \begin{bmatrix} 0 & 2 & 4 & 2 & 0 & 5 \\ 2 & 0 & 0 & 3 & 1 & 1 \\ 4 & 0 & 0 & 1 & 1 & 0 \\ 2 & 3 & 1 & 0 & 1 & 3 \\ 0 & 1 & 1 & 1 & 0 & 1 \\ 5 & 1 & 0 & 3 & 1 & 0 \end{bmatrix}$$

$$ODU2 = \begin{bmatrix} 0 & 1 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \quad ODU3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$ODU4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix}$$

MEDIUM TRAFFIC – 5 TBITS/S

$$ODU0 = \begin{bmatrix} 0 & 50 & 10 & 30 & 10 & 30 \\ 50 & 0 & 0 & 10 & 50 & 0 \\ 10 & 0 & 0 & 10 & 40 & 10 \\ 30 & 10 & 10 & 0 & 10 & 10 \\ 10 & 50 & 40 & 10 & 0 & 30 \\ 30 & 0 & 10 & 10 & 30 & 0 \end{bmatrix} \quad ODU1 = \begin{bmatrix} 0 & 20 & 40 & 20 & 0 & 50 \\ 20 & 0 & 0 & 30 & 10 & 10 \\ 40 & 0 & 0 & 10 & 10 & 0 \\ 20 & 30 & 10 & 0 & 10 & 30 \\ 0 & 10 & 10 & 10 & 0 & 10 \\ 50 & 10 & 0 & 30 & 10 & 0 \end{bmatrix}$$

$$ODU2 = \begin{bmatrix} 0 & 10 & 10 & 10 & 0 & 0 \\ 10 & 0 & 0 & 0 & 10 & 0 \\ 10 & 0 & 0 & 10 & 10 & 0 \\ 10 & 0 & 10 & 0 & 10 & 0 \\ 0 & 10 & 10 & 10 & 0 & 10 \\ 0 & 0 & 0 & 0 & 10 & 0 \end{bmatrix} \quad ODU3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10 & 0 & 0 & 10 \\ 0 & 10 & 0 & 0 & 10 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$ODU4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10 \\ 0 & 10 & 0 & 0 & 10 & 0 \end{bmatrix}$$

HIGH TRAFFIC – 10 TBITS/S

$$ODU0 = \begin{bmatrix} 0 & 100 & 20 & 60 & 20 & 60 \\ 100 & 0 & 0 & 20 & 100 & 0 \\ 20 & 0 & 0 & 20 & 80 & 20 \\ 60 & 20 & 20 & 0 & 20 & 20 \\ 20 & 100 & 80 & 20 & 0 & 60 \\ 60 & 0 & 20 & 20 & 60 & 0 \end{bmatrix} \quad ODU1 = \begin{bmatrix} 0 & 40 & 80 & 40 & 0 & 100 \\ 40 & 0 & 0 & 60 & 20 & 20 \\ 80 & 0 & 0 & 20 & 20 & 0 \\ 40 & 60 & 20 & 0 & 20 & 60 \\ 0 & 20 & 20 & 20 & 0 & 20 \\ 100 & 20 & 0 & 60 & 20 & 0 \end{bmatrix}$$

$$ODU2 = \begin{bmatrix} 0 & 20 & 20 & 20 & 0 & 0 \\ 20 & 0 & 0 & 0 & 20 & 0 \\ 20 & 0 & 0 & 20 & 20 & 0 \\ 20 & 0 & 20 & 0 & 20 & 0 \\ 0 & 20 & 20 & 20 & 0 & 20 \\ 0 & 0 & 0 & 0 & 20 & 0 \end{bmatrix} \quad ODU3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 20 & 0 & 0 & 20 \\ 0 & 20 & 0 & 0 & 20 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 20 & 0 & 0 & 0 \\ 0 & 20 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$ODU4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 20 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 20 \\ 0 & 20 & 0 & 0 & 20 & 0 \end{bmatrix}$$

TRANSPORT MODES

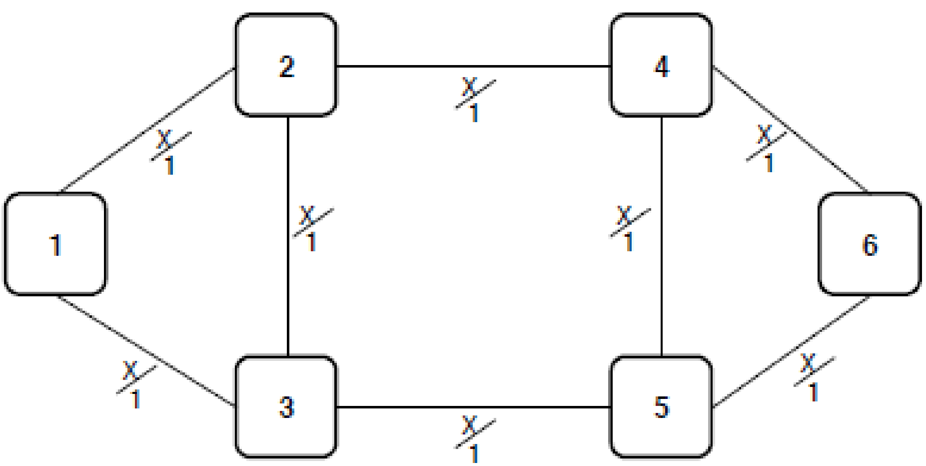
Although the same physical links are always the same traffic is carried out differently.

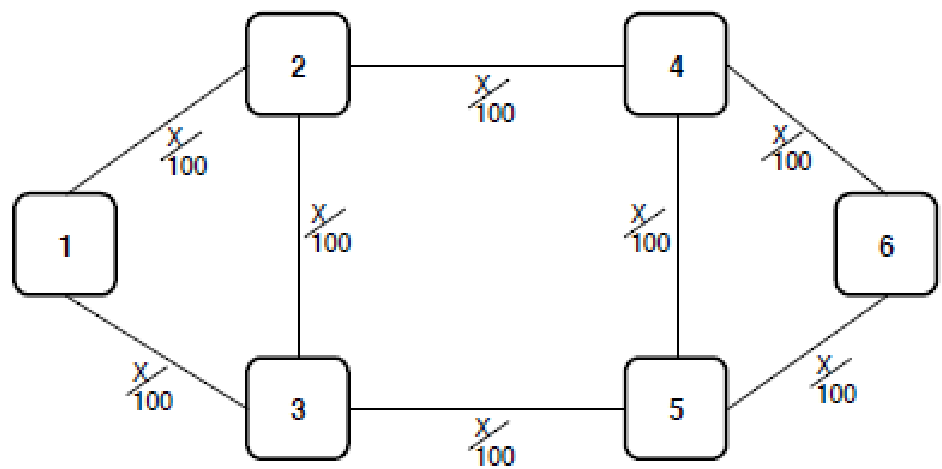
Depending on the number of conversions of an optical signal to the electrical domain, different modes of transport will appear.

- Opaque transport mode
- Transparent transport mode
- Translucent transport mode

OPAQUE TRANSPORT MODE

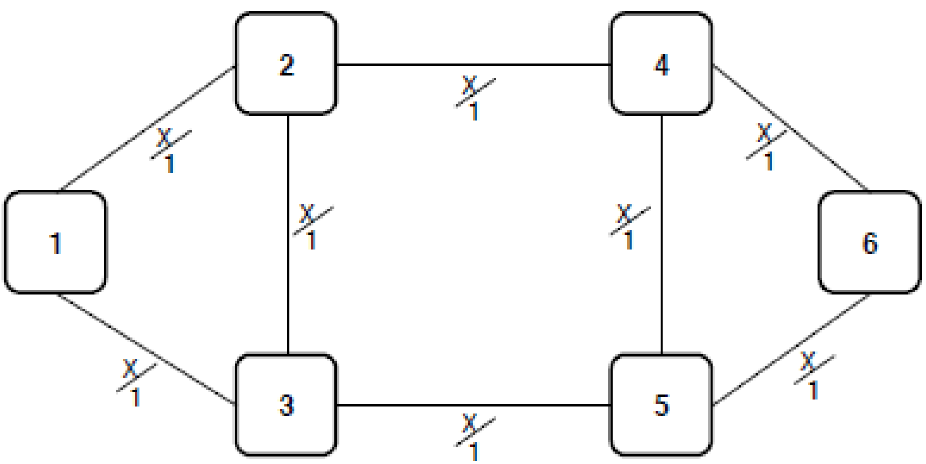
- The opaque transport mode performs OEO conversions on each intermediate node because of the need for converting to electronic domain.
- The optical and physical topologies are the same, causing each traffic route to match the link-to-link path imposed by fiber optics between each intermediate node to the destination.

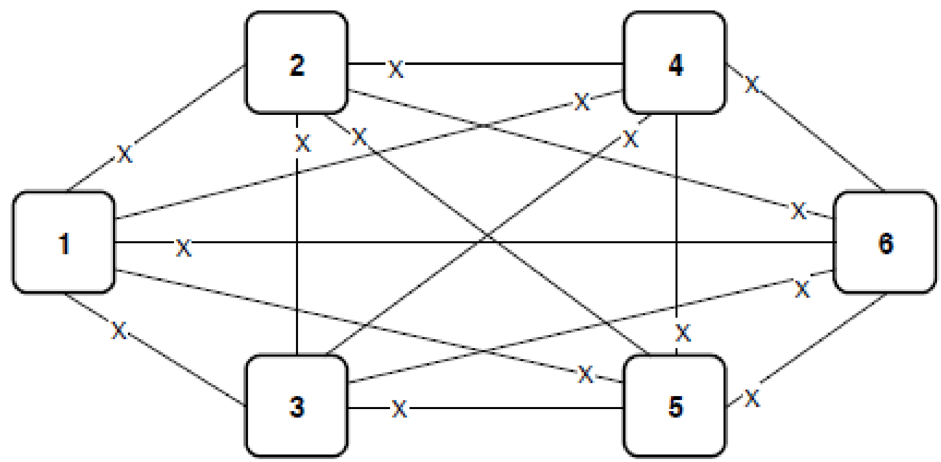




TRANSPARENT TRANSPORT MODE

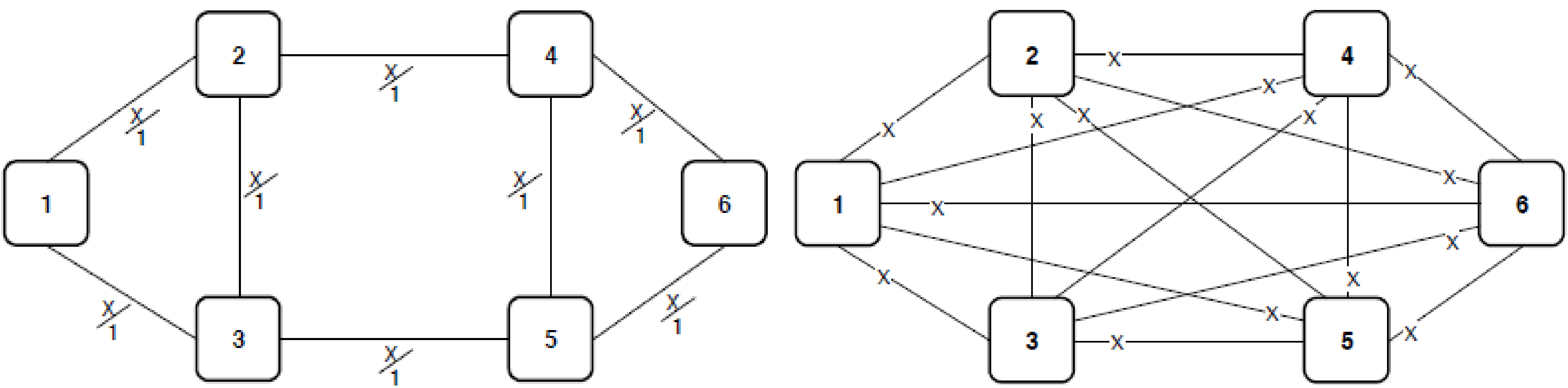
- In transparent transport mode, a route is only defined between source and destination nodes always in the optical domain.
- In this mode the physical and optical topologies are different.
- This type of network performs the OEO conversion only at the end nodes of the path.





TRANSLUCENT TRANSPORT MODE

- This mode of transport is a combination of the other two transport modes taking the respective advantages of both.
- The physical and optical topologies are different, the latter having several solutions.
- The OEO conversion is done in some intermediate places before arriving at its destination.



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CAPEX USING ILP MODELS

The telecommunications networks are formed by links and nodes, therefore, it is possible to define the CAPEX as the sum of the cost of the links and the cost of the nodes.

$$C_C = C_L + C_N$$

Link:

$$C_L = \sum_{i=1}^{N} \sum_{j=i+1}^{N} L_{ij}\left(2\gamma_0^{OLT} + 2\gamma_1^{OLT}\tau W_{ij} + 2N_{ij}^{R}c^{R}\right)$$

A link consists of two optical line terminals, has several amplifiers placed at a certain distance (span) and consists of several optical channels each with a certain wavelength.

$$N_{ij}^{R} = \sum_{i=1}^{N} \sum_{j=i+1}^{N} \left(\left\lceil \frac{len_{ij}}{span} \right\rceil - 1\right)$$

The number of amplifiers for each link is obtained by the length of a link and the distance between amplifiers (span).

Node:

$$C_N = C_{EXC} + C_{OXC}$$

The nodes have an electrical part and an optical part so the cost of the nodes is given by the sum of these two parts.

$$C_{EXC} = \sum_{n=1}^{N} N_{exc,n}\left(\gamma_{e0} + \sum_{c=-1}^{B} \gamma_{e1,c} P_{exc,c,n}\right)$$

$$C_{OXC} = \sum_{n=1}^{N} N_{oxc,n}\left(\gamma_{o0} + \gamma_{o1} P_{oxc,n}\right)$$

The electric and optical cost is the sum of the fixed cost of the electrical/optical connection with the total cost of all respective ports.

CAPEX USING ILP MODELS

- In this work we assume that the routing is performed by the ILP model instead of feeding it with candidate paths. The flow conservation constraints ensures that, for each (o,d) pair we route Z units of flow from node o to node d.

$$minimize \quad \left\{ \quad C_C \quad \right\}$$

$$subject\ to$$

$$\sum_{j=1\backslash\{o\}}^{N} f_{ij}^{od} = Z \qquad \forall (o,d) : o < d, \forall i : i = o \qquad (3.7)$$

$$\sum_{j=1\backslash\{o\}}^{N} f_{ij}^{od} = \sum_{j=1\backslash\{d\}}^{N} f_{ji}^{od} \qquad \forall (o,d) : o < d, \forall i : i \neq o, d \qquad (3.8)$$

$$\sum_{j=1\backslash\{d\}}^{N} f_{ji}^{od} = Z \qquad \forall (o,d) : o < d, \forall i : i = d \qquad (3.9)$$

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ILP – OPAQUE WITHOUT SURVIVABILITY

$$minimize \quad \left\{ \quad C_C \quad \right\}$$

subject to

$$\sum_{j=1 \setminus \{o\}}^{N} fb_{ij}^{od} = 1 \qquad \forall (o,d) : o < d, \forall i : i = o \qquad (4.2)$$

$$\sum_{j=1 \setminus \{o\}}^{N} fb_{ij}^{od} = \sum_{j=1 \setminus \{d\}}^{N} f_{ji}^{od} \qquad \forall (o,d) : o < d, \forall i : i \neq o, d \qquad (4.3)$$

$$\sum_{j=1 \setminus \{d\}}^{N} fb_{ji}^{od} = 1 \qquad \forall (o,d) : o < d, \forall i : i = d \qquad (4.4)$$

$$\sum_{o=1}^{N} \sum_{d=o+1}^{N} \left(fb_{ij}^{od} + fb_{ji}^{od} \right) \sum_{c=1}^{C} \left(B\left(c\right) D_{odc} \right) \leq \tau W_{ij} G_{ij} \qquad \forall (i,j) : i < j \qquad (4.5)$$

$$W_{ij} \leq K_{ij} L_{ij} \qquad \forall (i,j) : i < j \qquad (4.6)$$

$$fb_{ij}^{od}, fb_{ji}^{od}, L_{ij} \in \{0, 1\} \qquad \forall (i,j) : i < j, \forall (o,d) : o < d \qquad (4.7)$$

$$W_{ij} \in \mathbb{N} \qquad \forall (i,j) : i < j \qquad (4.8)$$

ILP – TRANSPARENT WITHOUT SURVIVABILITY

$$minimize \quad \{ \quad C_C \quad \}$$

subject to

$$\sum_{c=1}^{C} (B(c)\, D_{odc}) \leq \tau \lambda_{od} \qquad \forall (o,d) : o < d \qquad (4.16)$$

$$\sum_{j=1 \setminus \{o\}}^{N} f_{ij}^{od} = \lambda_{od} \qquad \forall (o,d) : o < d, \forall i : i = o \qquad (4.17)$$

$$\sum_{j=1 \setminus \{o\}}^{N} f_{ij}^{od} = \sum_{j=1 \setminus \{d\}}^{N} f_{ji}^{od} \qquad \forall (o,d) : o < d, \forall i : i \neq o, d \qquad (4.18)$$

$$\sum_{j=1 \setminus \{d\}}^{N} f_{ji}^{od} = \lambda_{od} \qquad \forall (o,d) : o < d, \forall i : i = d \qquad (4.19)$$

$$\sum_{o=1}^{N} \sum_{d=o+1}^{N} \left(f_{ij}^{od} + f_{ji}^{od} \right) \leq K_{ij} G_{ij} L_{ij} \qquad \forall (i,j) : i < j \qquad (4.20)$$

$$f_{ij}^{od}, f_{ji}^{od}, \lambda_{od} \in \mathbb{N} \qquad \forall (i,j) : i < j, \forall (o,d) : o < d \qquad (4.21)$$

ILP – TRANSLUCENT WITHOUT SURVIVABILITY

$$minimize \quad \{ \ C_C \ \}$$

subject to

$$\sum_{k=1\backslash\{o\}}^{N} Ls_{pk}^{odc} = D_{odc} \qquad \forall(o,d,c) : o < d, \forall p : p = o \qquad (4.33)$$

$$\sum_{k=1\backslash\{p,o\}}^{N} Ls_{pk}^{odc} = \sum_{k=1\backslash\{p,d\}}^{N} Ls_{kp}^{odc} \qquad \forall(o,d,c) : o < d, \forall p : p \neq o, d \qquad (4.34)$$

$$\sum_{k=1\backslash\{d\}}^{N} Ls_{kp}^{odc} = D_{odc} \qquad \forall(o,d,c) : o < d, \forall p : p = d \qquad (4.35)$$

$$\sum_{o=1}^{N} \sum_{d=o+1}^{N} (B(c)(Ls_{pk}^{odc} + Ls_{kp}^{odc})) \leq \tau\lambda_{pk} \qquad \forall(p,k) : p < k, \forall c \qquad (4.36)$$

$$\sum_{j=1\backslash\{p\}}^{N} f_{ij}^{pk} = \lambda_{pk} \qquad \forall(p,k) : p < k, \forall i : i = p \qquad (4.37)$$

$$\sum_{j=1\backslash\{p\}}^{N} f_{ij}^{pk} = \sum_{j=1\backslash\{k\}}^{N} f_{ji}^{pk} \qquad \forall(p,k) : p < k, \forall i : i \neq p, k \qquad (4.38)$$

$$\sum_{j=1\backslash\{k\}}^{N} f_{ji}^{pk} = \lambda_{pk} \qquad \forall(p,k) : p < k, \forall i : i = k \qquad (4.39)$$

ILP – TRANSLUCENT WITHOUT SURVIVABILITY

$$\sum_{p=1}^{N}\sum_{k=p+1}^{N}\left(f_{ij}^{pk}+f_{ji}^{pk}\right)\leq K_{ij}G_{ij}L_{ij} \qquad \forall(i,j):i<j \qquad (4.40)$$

$$f_{ij}^{pk},f_{ji}^{pk},Ls_{pk}^{odc},Ls_{kp}^{odc},\lambda_{pk}\in\mathbb{N} \qquad \forall(i,j):i<j,\forall(o,d):o<d \qquad (4.41)$$

$$L_{i,j}\in\{0,1\} \qquad \forall(i,j) \qquad (4.42)$$

ILP – OPAQUE WITH 1+1 PROTECTION

$$minimize \quad \left\{ \quad C_C \quad \right\}$$

subject to

$$\sum_{j=1\setminus\{o\}}^{N} fb_{ij}^{od} = 2 \qquad \forall(o,d) : o < d, \forall i : i = o \qquad (4.9)$$

$$\sum_{j=1\setminus\{o\}}^{N} fb_{ij}^{od} = \sum_{j=1\setminus\{d\}}^{N} f_{ji}^{od} \qquad \forall(o,d) : o < d, \forall i : i \neq o, d \qquad (4.10)$$

$$\sum_{j=1\setminus\{d\}}^{N} fb_{ji}^{od} = 2 \qquad \forall(o,d) : o < d, \forall i : i = d \qquad (4.11)$$

$$\sum_{o=1}^{N} \sum_{d=o+1}^{N} \left(fb_{ij}^{od} + fb_{ji}^{od} \right) \sum_{c=1}^{C} (B\left(c\right) D_{odc}) \leq \tau W_{ij} G_{ij} \qquad \forall(i,j) : i < j \qquad (4.12)$$

$$W_{ij} \leq K_{ij} L_{ij} \qquad \forall(i,j) : i < j \qquad (4.13)$$

$$fb_{ij}^{od}, fb_{ji}^{od}, L_{ij} \in \{0,1\} \qquad \forall(i,j) : i < j, \forall(o,d) : o < d \qquad (4.14)$$

$$W_{ij} \in \mathbb{N} \qquad \forall(i,j) : i < j \qquad (4.15)$$

ILP – TRANSPARENT WITH 1+1PROTECTION

$$minimize \quad \left\{ \quad C_C \quad \right\}$$

subject to

$$\sum_{c=1}^{C} (B(c)\, D_{odc}) \leq \tau \lambda_{od} \qquad \forall (o,d) : o < d \qquad (4.22)$$

$$\sum_{j=1 \setminus \{o\}}^{N} f_{ij}^{od} = \lambda_{od} \qquad \forall (o,d) : o < d, \forall i : i = o \qquad (4.23)$$

$$\sum_{j=1 \setminus \{o\}}^{N} f_{ij}^{od} = \sum_{j=1 \setminus \{d\}}^{N} f_{ji}^{od} \qquad \forall (o,d) : o < d, \forall i : i \neq o, d \qquad (4.24)$$

$$\sum_{j=1 \setminus \{d\}}^{N} f_{ji}^{od} = \lambda_{od} \qquad \forall (o,d) : o < d, \forall i : i = d \qquad (4.25)$$

$$\sum_{j=1 \setminus \{o\}}^{N} fp_{ij}^{od} = \lambda_{od} \qquad \forall (o,d) : o < d, \forall i : i = o \qquad (4.26)$$

$$\sum_{j=1 \setminus \{o\}}^{N} fp_{ij}^{od} = \sum_{j=1 \setminus \{d\}}^{N} fp_{ji}^{od} \qquad \forall (o,d) : o < d, \forall i : i \neq o, d \qquad (4.27)$$

ILP – TRANSPARENT WITH 1+1PROTECTION

$$\sum_{j=1\backslash\{d\}}^{N} fp_{ji}^{od} = \lambda_{od} \qquad \forall(o,d) : o < d, \forall i : i = d \qquad (4.28)$$

$$\sum_{o=1}^{N} \sum_{d=o+1}^{N} \left(f_{ij}^{od} + fp_{ij}^{od} \right) \leq \lambda_{od} \qquad \forall(o,d),(i,j) \qquad (4.29)$$

$$\sum_{o=1}^{N} \sum_{d=o+1}^{N} \left(f_{ij}^{od} + f_{ji}^{od} + fp_{ij}^{od} + fp_{ji}^{od} \right) \leq K_{ij} G_{ij} L_{ij} \qquad \forall(i,j) : i < j \qquad (4.30)$$

$$f_{ij}^{od}, f_{ji}^{od}, fp_{ij}^{od}, fp_{ji}^{od}, \lambda_{od} \in \mathbb{N} \qquad \forall(i,j) : i < j, \forall(o,d) : o < d \qquad (4.31)$$

$$L_{i,j} \in \{0,1\} \qquad \forall(i,j) \qquad (4.32)$$

ILP – TRANSLUCENT WITH 1+1 PROTECTION

$$minimize \quad \{ \quad C_C \quad \}$$

subject to

$$\sum_{k=1 \setminus \{o\}}^{N} Ls_{pk}^{odc} = D_{odc} \qquad \forall (o,d,c) : o < d, \forall p : p = o \qquad (4.43)$$

$$\sum_{k=1 \setminus \{p,o\}}^{N} Ls_{pk}^{odc} = \sum_{k=1 \setminus \{p,d\}}^{N} Ls_{kp}^{odc} \qquad \forall (o,d,c) : o < d, \forall p : p \neq o, d \qquad (4.44)$$

$$\sum_{k=1 \setminus \{d\}}^{N} Ls_{kp}^{odc} = D_{odc} \qquad \forall (o,d,c) : o < d, \forall p : p = d \qquad (4.45)$$

$$\sum_{k=1 \setminus \{o\}}^{N} Lsp_{pk}^{odc} = D_{odc} \qquad \forall (o,d,c) : o < d, \forall p : p = o \qquad (4.46)$$

$$\sum_{k=1 \setminus \{p,o\}}^{N} Lsp_{pk}^{odc} = \sum_{k=1 \setminus \{p,d\}}^{N} Lsp_{kp}^{odc} \qquad \forall (o,d,c) : o < d, \forall p : p \neq o, d \qquad (4.47)$$

$$\sum_{k=1 \setminus \{d\}}^{N} Lsp_{kp}^{odc} = D_{odc} \qquad \forall (o,d,c) : o < d, \forall p : p = d \qquad (4.48)$$

$$(Ls_{pk}^{odc} + Lsp_{pk}^{odc}) \leq D_{odc} \qquad \forall (p,k), \forall (o,d,c) : o < d \qquad (4.49)$$

ILP – TRANSLUCENT WITH 1+1 PROTECTION

$$\sum_{o=1}^{N}\sum_{d=o+1}^{N}(B(c)(Ls_{pk}^{odc}+Ls_{kp}^{odc}+Lsp_{pk}^{odc}+Lsp_{kp}^{odc}))\leq\tau\lambda_{pk} \qquad \forall(p,k):p<k,\forall(c) \quad (4.50)$$

$$\sum_{j=1\backslash\{p\}}^{N} f_{ij}^{pk}=\lambda_{pk} \qquad \forall(p,k):p<k,\forall i:i=p \quad (4.51)$$

$$\sum_{j=1\backslash\{p\}}^{N} f_{ij}^{pk}=\sum_{j=1\backslash\{k\}}^{N} f_{ji}^{pk} \qquad \forall(p,k):p<k,\forall i:i\neq p,k \quad (4.52)$$

$$\sum_{j=1\backslash\{k\}}^{N} f_{ji}^{pk}=\lambda_{pk} \qquad \forall(p,k):p<k,\forall i:i=k \quad (4.53)$$

$$\sum_{p=1}^{N}\sum_{k=p+1}^{N}\left(f_{ij}^{pk}+f_{ji}^{pk}\right)\leq K_{ij}G_{ij}L_{ij} \qquad \forall(i,j):i<j \quad (4.54)$$

$$f_{ij}^{pk},f_{ji}^{pk},Ls_{pk}^{odc},Ls_{kp}^{odc},\lambda_{pk}\in\mathbb{N} \qquad \forall(i,j):i<j,\forall(o,d):o<d \quad (4.55)$$

$$L_{i,j}\in\{0,1\} \qquad \forall(i,j) \quad (4.56)$$

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OPAQUE TRANSPORT MODE

without survivability			
	ILP	Analytical	Heuristics
Low scenario	11 266 590 €	10 115 720 € (-10%)	14 382 590 € (+28%)
Medium scenario	90 605 900 €	92 937 260 € (+3%)	92 405 900 € (+2%)
High scenario	178 231 800 €	184 794 340 € (+4%)	178 834 200 € (0%)

with 1+1 protection			
	ILP	Analytical	Heuristics
Low scenario	26 982 590 €	25 454 380 € (-6%)	28 182 590 € (+4%)
Medium scenario	239 405 900 €	241 483 260 € (+1%)	239 405 900 € (0%)
High scenario	477 031 800 €	481 107 780 € (+1%)	477 034 200 € (0%)

TRANSPARENT TRANSPORT MODE

without survivability			
	ILP	Analytical	Heuristics
Low scenario	30 317 590 €	10 827 792 € (-64%)	30 317 590 € (0%)
Medium scenario	96 830 900 €	99 189 607 € (+2%)	99 700 900 € (+3%)
High scenario	180 471 800 €	197 179 213 € (+9%)	186 006 800 € (+3%)

with 1+1 protection			
	ILP	Analytical	Heuristics
Low scenario	72 467 590 €	25 449 133 € (-65%)	72 527 590 € (0%)
Medium scenario	239 540 900 €*	239 061 736 € (0%)	242 410 900 € (+1%)
High scenario	448 806 800 €*	476 119 473 € (+6%)	454 341 800 € (+1%)

* It is not an optical solution. Best result after one week

TRANSLUCENT TRANSPORT MODE

without survivability		
	ILP	Heuristics
Low scenario	7 531 590 €	11 592 590 € (+54%)
Medium scenario	43 427 900 €	49 125 900 € (+13%)
High scenario	85 988 800 €	93 921 800 € (+9%)

with 1+1 protection		
	ILP	Heuristics
Low scenario	12 567 590 €	29 682 590 € (+136%)
Medium scenario	96 665 900 €	99 375 900 € (+3%)
High scenario	195 051 800 €*	186 381 800 € (-4%)

* It is not an optical solution. Best result after one week

- Motivation
- Network specification
- Capital expenditures
- Integer linear programming
- Comparative analysis
- Conclusions

COST PER BIT

without survivability			
	Low traffic scenario	**Medium traffic scenario**	**High traffic scenario**
Opaque	22.533 €/Gbit/s	18.121 €/Gbit/s	17.823 €/Gbit/s
Transparent	60.630 €/Gbit/s	19.366 €/Gbit/s	18.047 €/Gbit/s
Translucent	15.063 €/Gbit/s	8.685 €/Gbit/s	8.599 €/Gbit/s

With 1+1 protection			
	Low traffic scenario	**Medium traffic scenario**	**High traffic scenario**
Opaque	53.963 €/Gbit/s	47.881 €/Gbit/s	47.703 €/Gbit/s
Transparent	144.935 €/Gbit/s	47.908 €/Gbit/s	44.880 €/Gbit/s
Translucent	25.135 €/Gbit/s	19.333 €/Gbit/s	19.505 €/Gbit/s

CONCLUSIONS

- **ILP models have been developed for all transport modes without survivability and with 1+1 protection where each model contains a set of constraints.**

- For a comparative analysis is used the network **CAPEX analytically calculated** and the results obtained with the **heuristic algorithms already created**.

- From the analytical model we can state, taking into account the **margin of error of 10%,** that all formulas and deductions for the opaque and transparent mode give us **a value close to the optimum.**

CONCLUSIONS

- The **heuristic algorithms** are **a good solution for realistic and more complex** networks because it obtains results **close to the optimal solutions** obtained by the ILPs.

- We can say that **the best ILP model is the translucent mode,** because it provides a **lower cost than the other modes** allowing to carry more traffic.

- Regardless of the model chosen, it is **always more advantageous to put high traffic on the network.**

THANK YOU!