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

CONTENTS

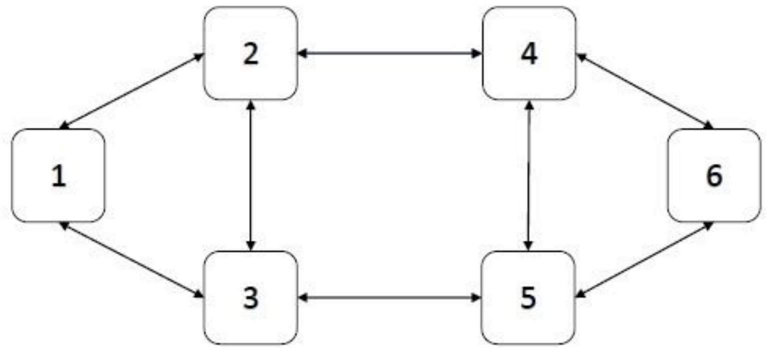
MOTIVATION

- The crucial premise for network operators to choose the technology and architecture to deploy is the **cost minimization.**
- **Planning tools** play a very important role and directly **affect the competitiveness** of a **system vendor** or **network operator.** It is used in the various stages of the telecommunications business.
- One of **the tools used in planning** transport networks **is the integer linear programming models.** These models offer great solutions and allow quick and easy changes.

- Motivation
- Reference network
- Capital expenditures
- Integer linear programming
- Comparative analysis
- Conclusions

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

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

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

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

MEDIUM TRAFFIC

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

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

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

HIGH TRAFFIC

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

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

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

- Motivation
- Reference network
- Capital expenditures
- Integer linear programming
- Comparative analysis
- Conclusions

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

Opaque mode:

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c}$$

$$P_{exc,-1,n} = \sum_{j=1}^{N} w_{nj}$$

Number of long-reach ports of the electrical switch with bit-rate -1 in node n i.e. number of line ports.

In opaque mode there is no optical part so there are no optical switch ports.

Transparent mode:

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c}$$

$$P_{exc,-1,n} = \sum_{j=1}^{N} \lambda_{nj}$$

$$P_{oxc,n} = \sum_{j=1}^{N} f_{nj}^{od} + \sum_{j=1}^{N} \lambda_{nj}$$

Translucent mode:

$$P_{exc,c,n} = \sum_{d=1}^{N} D_{nd,c}$$

$$P_{exc,-1,n} = \sum_{k=1}^{N} \lambda_{nk}$$

$$P_{oxc,n} = \sum_{j=1}^{N} f_{nj}^{pk} + \sum_{k=1}^{N} \lambda_{nk}$$

Number of short-reach ports of the electrical switch with bit-rate c in node n i.e. number of tributary ports.

Number of long-reach ports of the electrical switch with bit-rate -1 in node n i.e. number of add ports.

Number of long-reach ports of the optical switch in node n i.e. number of line ports and adding ports of node n.

CAPEX – USING ANALYTICAL MODELS

This time the calculations are made in an analytical way in order to get a different point of view and expected similar results.

$$C_C = C_L + C_N$$

Link:

$$C_L = (2L\gamma_0^{OLT}) + (2L\gamma_1^{OLT}\tau < w >) + (2N^R c^R)$$

The cost of the link is calculated through total values and assuming analytically calculated average values.

$$< w >= \left(\frac{\lceil D\times < h >\rceil}{L_u}\right)(1+ < k >)$$

$$D = \left(\frac{1}{2}\right)(1+\xi)\left(\frac{T_1}{\tau}\right)$$

Node:

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

The cost of the nodes is calculated through the sum of electrical part and optical part.

$$C_{exc} = N \times (\gamma_{e0} + (\gamma_{e1}\tau < P_{exc} >)) + \gamma_{e1}P_{TRIB}$$

$$C_{oxc} = N \times (\gamma_{o0} + (\gamma_{o1} < P_{oxc} >))$$

The electric and optical cost is the total nodes times the fixed cost of the electrical/optical connection and the cost of average number of respective ports.

CAPEX – USING ANALYTICAL MODELS

Opaque mode:

This mode of transport there is no optical cost.

We are assuming that the grooming coefficient has value 1.

We also assuming that the survivability coefficient is zero when it is without survivability or $< kp >$ when it is with 1+1 protection.

$$< P_{exc} >=< d >< h > (1+ < k >)$$

$$< d >= \frac{D}{N}$$

Transparent mode:

In this mode of transport there we are assuming that the grooming coefficient has value 1,25.

We also assuming that the survivability coefficient is zero when it is without survivability or $< kp >$ when it is with 1+1 protection.

$$< kp >= \frac{< h' >}{< h >}$$

$$< P_{exc} >=< d >$$

$$< P_{oxc} >=< d > [1 + (1+ < k >) < h >]$$

- Motivation
- Reference network
- Capital expenditures
- Integer linear programming
- Comparative analysis
- Conclusions

ILP – OPAQUE WITHOUT SURVIVABILITY

$$minimize \quad \left\{ \; C_C \; \right\} \tag{4.1}$$

subject to

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

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

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

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

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

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

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

ILP – OPAQUE WITH 1+1 PROTECTION

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

subject to

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

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

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

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

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

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

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

ILP – TRANSPARENT WITHOUT SURVIVABILITY

$$\textit{minimize} \quad \{ \; C_C \; \}$$

subject to

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

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

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

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

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

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

ILP – TRANSPARENT WITH 1+1PROTECTION

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

subject to

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

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

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

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

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

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

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

ILP – TRANSPARENT WITH 1+1PROTECTION

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

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

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

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

ILP – TRANSLUCENT WITHOUT SURVIVABILITY

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

subject to

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

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

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

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

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

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

ILP – TRANSLUCENT WITHOUT SURVIVABILITY

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

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

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

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

ILP – TRANSLUCENT WITH 1+1 PROTECTION

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

subject to

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

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

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

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

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

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

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

ILP – TRANSLUCENT WITH 1+1 PROTECTION

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

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

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

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

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

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

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

MASTER CONCLUSIONS

	Low traffic scenario	Medium traffic scenario	High traffic scenario
Opaque without survivability	22.533 Gbits/s	18.121 Gbits/s	17.823 Gbits/s
Opaque with 1+1 protection	53.963 Gbits/s	47.881 Gbits/s	47.703 Gbits/s
Transparent without survivability	60.630 Gbits/s	19.366 Gbits/s	18.047 Gbits/s
Transparent with 1+1 protection	144.935 Gbits/s	47.908 Gbits/s	44.880 Gbits/s
Translucent without survivability	15.063 Gbits/s	8.685 Gbits/s	8.599 Gbits/s
Translucent with 1+1 protection	25.135 Gbits/s	19.333 Gbits/s	19.505 Gbits/s

- Motivation
- Reference network
- Capital expenditures
- Integer linear programming
- Comparative analysis
- Conclusions

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 € (0,3%)

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 € (0,7%)	239 405 900 € (0%)
High scenario	477 031 800 €	481 107 780 € (0,8%)	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 € (2,4%)	99 700 900 € (3%)
High scenario	180 471 800 €	197 179 213 € (9,2%)	186 006 800 € (3%)

with 1+1 protection			
	ILP	Analytical	Heuristics
Low scenario	72 467 590 €	25 449 133 € (65%)	72 527 590 € (0,1%)
Medium scenario	239 540 900 €*	239 061 736 € (0,2%)	242 410 900 € (1,2%)
High scenario	448 806 800 €*	476 119 473 € (6%)	454 341 800 € (1,2%)

TRANSLUCENT TRANSPORT MODE

without survivability		
	ILP	Heuristics
Low scenario	7 531 590 €	11 592 590 € (53,9%)
Medium scenario	43 427 900 €	49 125 900 € (13,2%)
High scenario	85 988 800 €	93 921 800 € (9,2%)

with 1+1 protection		
	ILP	Heuristics
Low scenario	12 567 590 €	29 682 590 € (136%)
Medium scenario	96 665 900 €	99 375 900 € (2,8%)
High scenario	195 051 800 €*	186 381 800 € (4,4%)

- Motivation
- Reference network
- Capital expenditures
- Integer linear programming
- Comparative analysis
- Conclusions

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.**
- Heuristic algorithms are **a good solution for opaque and transparent mode** with the exception of opaque mode without survivability for low scenarios. The case of the **translucent at this time is not a good solution.**
- 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!