Using GRASP and GA to design resilient and cost-effective IP/MPLS networks

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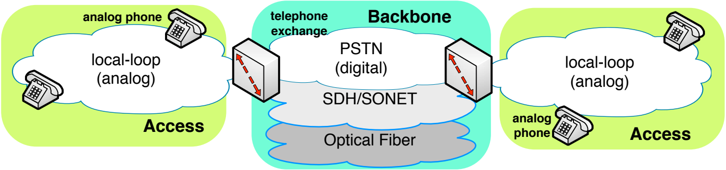
The digitization of the network

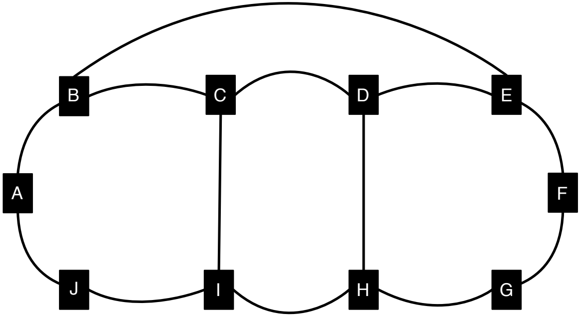
- After a hundred years of expansion and evolution the telephone service was digitized.
- Standard phone calls used 64Kbps TDM streams.
- These voice-circuits were routed among TDM switches using SDH/SONET digital transport containers.



- Access portions remained analog (copper-lines).
- Transport networks were supported over optical fiber networks.
- Bringing highly available connections of high signal-noise ratio.

Automatic Protection Switching

APS is the native local-protection scheme for optical networks. It is based on an underlying ring structure. For instance:



For this physical structure.

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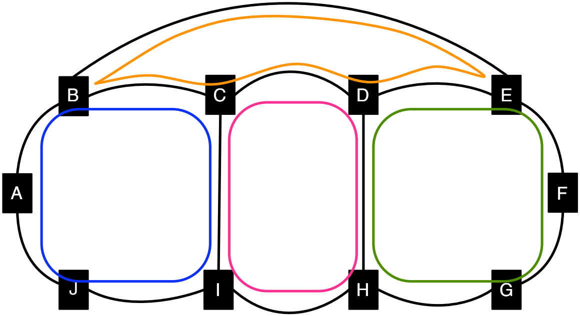

That is a possible rings assignment.

Automatic Protection Switching

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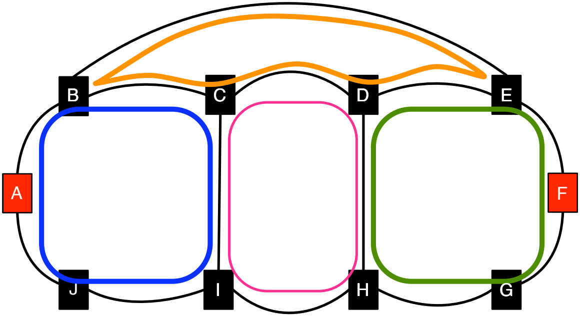
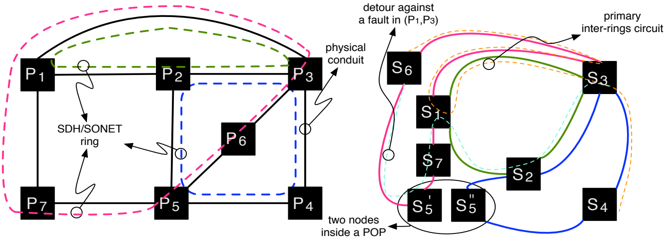


And a circuit between A and F could be deployed over the remarked rings or other combination.

Design of optical networks

- A standard STM-4/OC-12 TDM link supports up to 9,400 simultaneous phone-calls (1M inhabitants city).
- The design of the optical networks was then guided by cost and availability concerns.
- Demand and capacity were second order priorities.



- The transport network provided the resiliency (1+1), over a sequence of physically-independent logical rings/cycles.

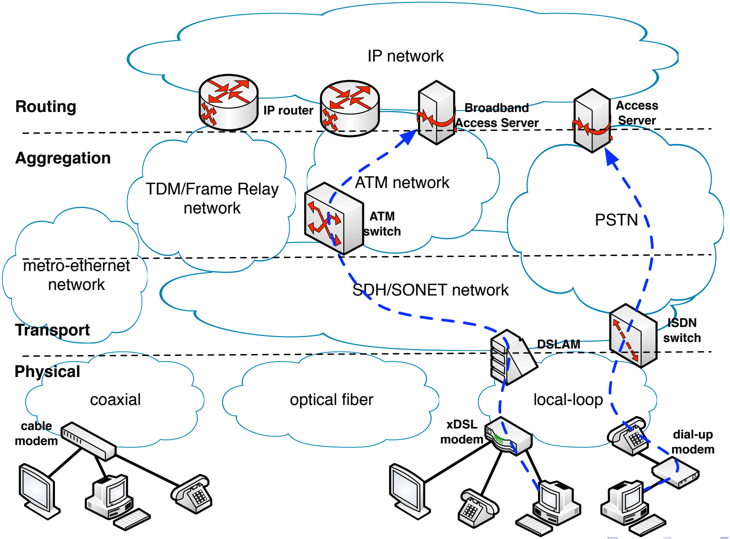
Design of optical networks

- In order to protect circuits between POPs, their paths should be spanned by a sequence of cycles.
- Some theoretical results (Berge et al.) bind this attribute with the connectivity degree between points.
- The higher the connectivity degree, the higher the number of cycles spanning certain number of nodes, and the higher the number of elements coverable with a cycle.
- Hence, by keeping a correspondence between the importance of the nodes and the connectivity degree among them, the quality of the optical network was guaranteed.
- This is the kind of single layer network design problems for which MW2CSN, STNSNP, kNCON and GSP were developed.
- Connectivity aside, the coordination between optical and transport network staffs was minimal.

Overlay networks

- Digital transport networks promoted overlay networks.
- An overlay network is a network that is built on the top of another one, i.e., the connections between nodes are implemented as services of an existing network.
- Internet has been an overlay network since its birth (dial-up access) till the present days (FTTH/xDSL).
- VPNs also were born and still are overlay networks.
- A decade ago there were many technological overlays.
- And many promising technologies (Frame Relay, ATM), designed to be the transport standard, became obsolete.
- Within an overlay network a single fault usually affects many connections, so existing models are not longer appropriate.

Overlay networks



The IP age and the surge of MPLS

- Since its birth, the traffic of Internet has been doubling itself year after year (it surpassed the voice traffic by the 90's).
- Today, some NAPs generate by themselves, tens of thousands of times the voice traffic of an entire city.
- Progressively, traffic and IP became synonyms, and the existence of intermediate overlays appeared unnecessary.
- Some equipment providers extended traditional IP routers to IP/MPLS switches, which added:
  1. Native support to VPNs (IPv4, IPv6 and Ethernet)
  2. Transparent transport to other protocols (Ethernet, ATM, Frame Relay and TDM circuits)
  3. Protection mechanisms whose performance ($\leq$ 50ms) is equivalent to that of SDH/SONET
- Legacy services (telephony) are being moved to the IP layer.

Impact over the optical network

- The exponential growth of Internet traffic pressures over the resources of the optical layer.
- But the bandwidth of optical fibers is far from exhausted.
- The bit-rate for the network interfaces has been growing along years (100Mbps, 1Gbps, 10Gbps, 40Gbps, 100Gbps).
- So has been the number of virtual fibers per physical ones.
- DWDM allows multiplexing many connections over one single cable of optical fiber using different wavelengths.
- Hence, DWDM multiplies the number of optical fibers without changing the physical topology.
- While inherits TDM protection schemes.
- Important portions of optical networks designed to fulfill the telephone service, are being used to support the Internet.

Warped premisses

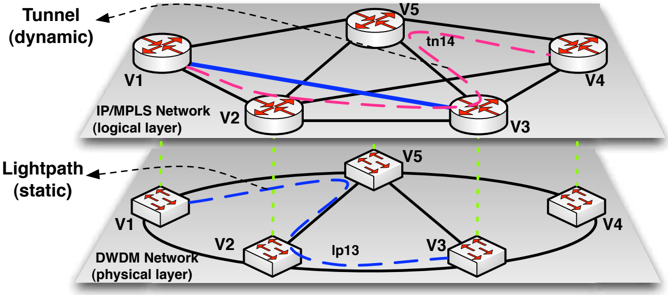
Several premisses have changed since most portions of optical networks were deployed:

1. Over 90% of the phone traffic is local. Besides of being thousands of times bigger, Internet traffic is international.
2. International phone calls were routed over satellite links. Internet links are supported over optical fiber.
3. The core of backbones were mostly set arbitrarily, thus they are likely misplaced.
4. Previous technologies (e.g. ATM, TDM switches) spurred the existence of centralized functions.
5. IP/MPLS provides protection mechanisms competitive in performance and more efficient than TDM/DWDM.

It becomes necessary to reassess the overall network design.

What services do these layers provide?

- In our models, the physical/optical layer provides unprotected point-to-point optical connectivity.
- Any logical link needs an optical implementation (*lightpath*).



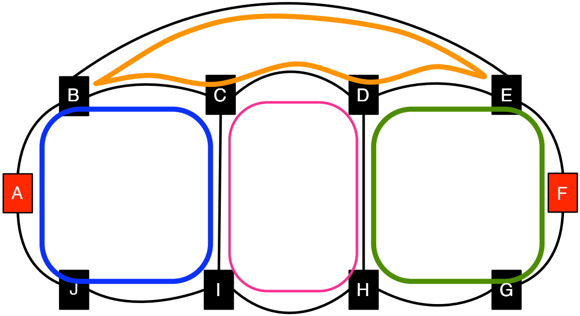
- Traffic is relayed and protected across the logical layer.
- Through the usage of *tunnels*.

IP/MPLS protection mechanisms

- The protection of each IP/MPLS tunnel is determined by the rules to construct its paths.
- Each tunnel has an attached list of rules, which determine its logical paths.
- The first operative path of each list is chosen.
- The easiest rule is LDP, which copies the internal routing protocol (SPF). It is dynamic but doesn't support traff-eng.
- Traffic engineering requires RSVP-TE. Typical rules for traff-eng tunnels are:
  1. An explicit list of intermediate nodes.
  2. CSPF (constraint based routing). A variant of SPF that allows using: capacity, usage, delay or administrative labels for links.
  3. A loose list of intermediate nodes/hops.

IP/MPLS protection flexibility

Combining these mechanisms, any APS protection scheme is replicable. For instance:



The previously schematized APS protection for a circuit between A an F could be replicated over MPLS just by coping the topology,....

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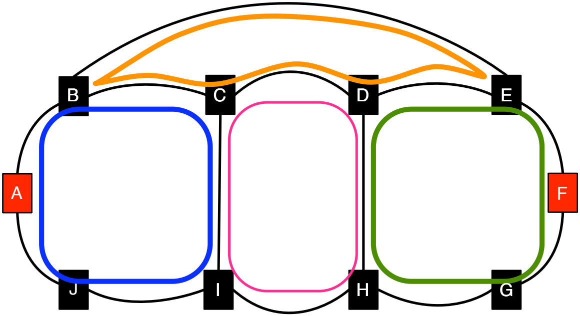

...coloring the links, and by setting up a tunnel through a combination of loose hops and color-constrained routing.

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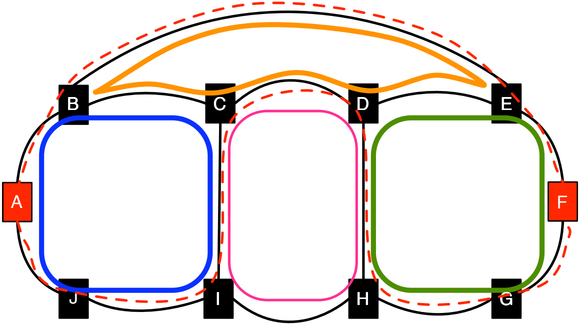

But the same degree of protection could have been achieved end-to-end by setting these two paths.

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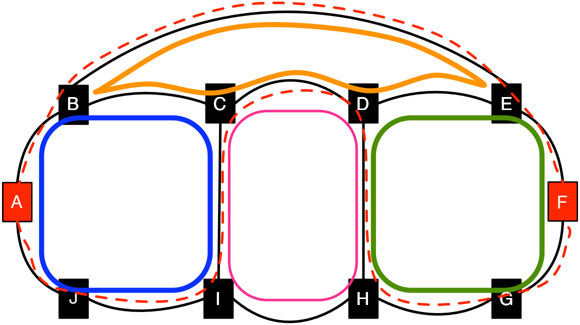

This configuration requires fewer links (B-C, D-E) and it is more efficient in terms of resources. So we decided not to emulate APS.

MORNDP variants

To fix a model we should establish a protection scheme

Active/Standby Protection

- This model relies on two paths for each tunnel
- These paths must be physically-independent
- Paths are defined hop-by-hop
- The spare capacity is shared among backup paths

Free Routing Protection

- This model allows an unlimited number of paths
- One per each physical failure
- For each failure the arrangement of paths must be fully operational
- The spare capacity is shared among backup paths

Whatever the chosen protection, it must be coordinated with the physical implementation.

ASP and FRP MIP formulations (parameters)

- V, P and L respectively correspond to the set of: nodes, physical and logical links. Nodes and physical links are fixed while logical link are only potential.
- Each physical link (ij) has a known positive length l_{ij}.
- Those logical links used in a solution should have one capacity within the set $\hat{B} = \{b_1, \ldots, b_{\bar{B}}\}$.
- According on the capacity $b \in \hat{B}$ selected to implement a logical link, there is a known per-distance cost c_b for it, and there is also a physical path to determine.
- The value of the parameter d_{pq} corresponds to the demand to satisfy between nodes p and q.

ASP and FRP MIP formulations (variables)

- τ_{pq}^{b} indicates that whether the capacity $b \in \hat{B}$ was chosen to implement the logical link (pq).
- The boolean variable y_{pq}^{ij} indicates that the link (ij) is in the physical path that implements the logical link (pq).
- For any demand d_{rs} the ASP model allows two logical paths. The boolean variable ${}^{rs}x_{pq}^{h}$ indicates whether the logical link (pq) is used for either the active or the standby $(h \in \{1, 2\})$ path throughout which the demand d_{rs} is satisfied.
- The FRP model allows as many paths as physical links, that is, as potential single failures. The boolean variable ${}^{rs}x_{pq}^{ij}$ indicates that the logical link (pq) is used to satisfy the demand d_{rs} when the physical link (ij) has failed.

ASP MIP formulations (constraints and objective)

$$
\left\{
\begin{array}{lll}
\sum_{b\in\hat{B}} \tau^b_{pq} \le 1 & \forall (pq)\in L. & (i)\\
\sum_{j/(pj)\in P} y^{pj}_{pq} = \sum_{b\in\hat{B}} \tau^b_{pq} & \forall (pq)\in L. & (ii)\\
\sum_{i/(iq)\in P} y^{iq}_{pq} = \sum_{b\in\hat{B}} \tau^b_{pq} & \forall (pq)\in L. & (iii)\\
\sum_{j/(ij)\in P} y^{ij}_{pq} = 2\theta^i_{pq} & \forall (pq)\in L, \forall i\in V, i\neq p, i\neq q. & (iv)\\
y^{ij}_{pq} - y^{ji}_{pq} = 0 & \forall (pq)\in L, \forall (ij)\in P. & (v)\\
\tau^b_{pq},\, y^{ij}_{pq},\, \theta^i_{pq} \in \{0,1\} & \forall (pq)\in L, \forall (ij)\in P\ \forall b\in\hat{B}, \forall i\in V. & (vi)
\end{array}
\right.
$$

$$
\left\{
\begin{array}{lll}
\min \sum_{\substack{(pq)\in L\\ (ij)\in P\\ b\in\hat{B}}} c_b l_{ij}\cdot {}^{b}\eta^{ij}_{pq} & & (i)\\
{}^{b}\eta^{ij}_{pq} \ge \tau^b_{pq} + y^{ij}_{pq} - 1 & \forall (pq)\in L, \forall (ij)\in P, \forall b\in\hat{B}. & (ii)\\
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{}^{rs}x^1_{pq} + y^{ij}_{pq} + {}^{rs}\lambda^{ij}_{pq} \le 2 & \forall d_{rs}>0, \forall (pq)\in L, \forall (ij)\in P. & (i)\\
{}^{rs}x^2_{\bar{p}\bar{q}} + y^{ij}_{\bar{p}\bar{q}} - {}^{rs}\lambda^{ij}_{pq} \le 1 & \forall d_{rs}>0, \forall (pq)\in L, \forall (ij)\in P, \forall (\bar{p}\bar{q})\in L. & (ii)\\
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Complexity analysis

ASP and FRP are NP-Hard (1)

On both models there is a polynomial reduction of 2ECSS to the subproblem of mapping the logical over the physical layer.

ASP and FRP are NP-Hard (2)

On both models there is a polynomial reduction of NPP to the subproblem of routing demands over the logical layer.

FRP is a relaxation of ASP

Up from a feasible solution of ASP, we can always determine a feasible configuration for FRP.

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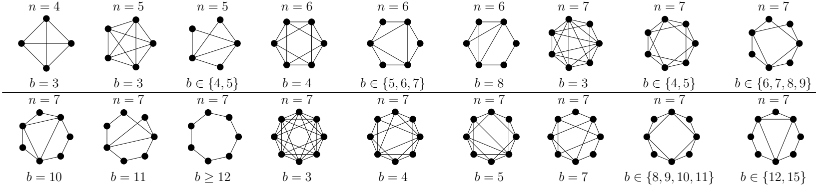
Exact solutions for CYCLE-FRP-MORNDP with CPLEX

We call CYCLE-FRP-MORNDP to those instances of FRP where: $P = \mathcal{C}_n$, $L = \mathcal{K}_n$, $l_{ij} = 1$, $\hat{B} = \{b\}$ and $d_{pq} = 1$.



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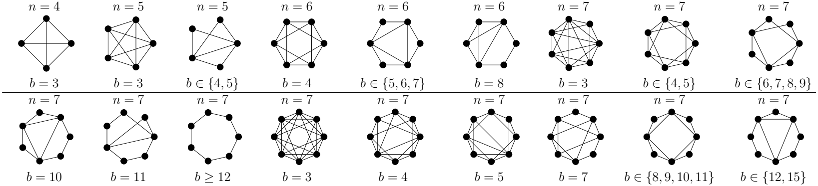


These are the exact solutions found with CPLEX.

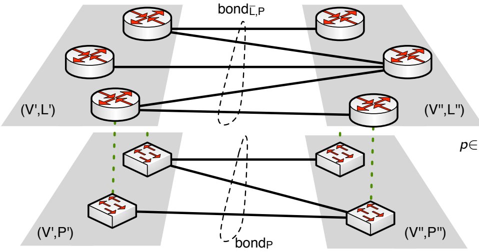
$\lvert V \rvert$	b_1 *range*	*number of variables*	*number of constraints*	*final time minus initial time (hh:mm:ss)*
5	2 - 6	1230	1640	00:00:00 - 000:00:11
6	3 - 9	3390	4035	00:00:02 - 000:19:31
7	2 - 12	7896	8652	00:00:05 - 087:19:05
8	3 - 16	16296	16772	00:00:02 - 100:10:17

And these are the corresponding times spent.

Additional theoretical results

Necessary condition

Extending the *cut-set* definition to a multilayer network, we found a necessary condition that any bond of a feasible solution must hold.



$$\sum_{p \in V', q \in V''} d_{pq} \leq b_{\bar{B}} \left\lfloor \frac{|bond_{\bar{L},P}|(|bond_P| - 1)}{|bond_P|} \right\rfloor$$

This condition was extensively used to find lower bounds.

Additional theoretical results

Necessary condition

Extending the *cut-set* definition to a multilayer network, we found a necessary condition that any bond of a feasible solution must hold.

Theoretical exact solutions

We proved that $\bar{L} = \mathcal{C}_n$ is optimal for CYCLE-FRP/ASP when either $b \geq n^2/4$ and n is even or $b \geq (n^2 - 1)/4$ and n is odd.

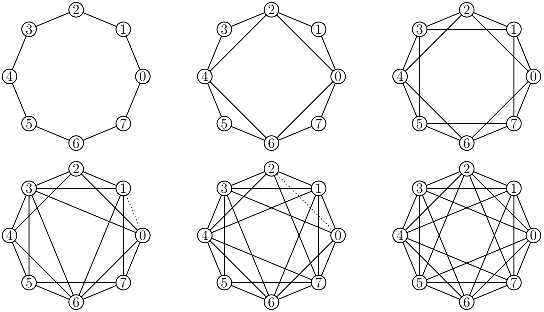
Theoretical exact solutions

Also proved that $\bar{L} = \mathcal{K}_n$ is optimal for CYCLE-FRP when $b = 2$ and n is odd, whereas $\bar{L} = \mathcal{K}_n^-$ is feasible when $b = 3$ and n is even.

These results encouraged us to go further into the theoretical analysis.

Additional theoretical results

Most recently we found a family of graphs cycle-frp(n, b) that spans previous solutions and is also optimal for $5 \leq n \leq 30$ when $(n, b) \notin \{(5,3),(7,3),(8,4),(10,5),(12,3),(20,25)\}$.



In order to tackle down this problem for real applications, we should rely on other computational tools.

Usage of metaheuristics

- Several heuristics and metaheuristics were used to find solutions to instances of both models.
- Some heuristics are based on exact methods.
- CPLEX was used as the core optimizer.
- We also tried: SA, VNS, EA, TS and GRASP.
- Best solutions for ASP model were found with a mix of EA and Tabu Search.
- For the FRP variant, only GRASP succeeded to solve instances with more than 20 nodes.

Algoritmos Evolutivos

- Son métodos aleatorios (aunque pueden usarse seeds) que emulan el proceso natural de selección y evolución.
- Se basan en *poblaciones* y no tienen *memoria*.

```
Initialize(P(0));
generation ← 0;
while not stopcriteria do
    evaluate(P(generation));
    parents ← selection(P(generation));
    offspring ← variation operators(parents);
    newpop ← replacement(offspring, P(generation));
    generation++;
    P(generation) ← newpop;
return best solution ever found.
```

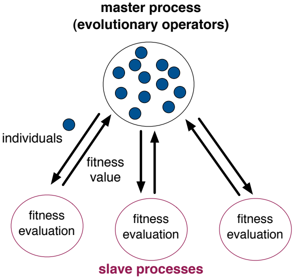
- Es un método iterativo donde en cada iteración (generación) se aplican operadores estocásticos a un pool de individuos.

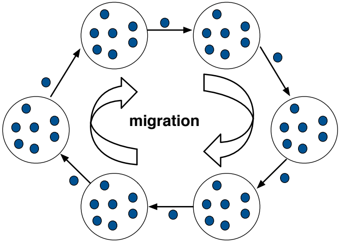
Algoritmos Evolutivos

- Cada individuo en la población es una versión codificada de una solución factible del problema.
- La población inicial se genera con un método aleatorio y/o una heurística específica para el problema.
- La selección (evaluación) se realiza en base al *fitness*, una métrica relacionada al objetivo buscado.
- Los individuos seleccionados se diversifican mediante operadores (cruzamiento, mutaciones, otros específicos).
- El criterio de parada responde a una combinación de:
    1. Tiempo de ejecución o límite de generaciones
    2. Nivel de calidad alcanzado en la solución
    3. Una situación de estancamiento

Algoritmos Evolutivos

Son especialmente populares cuando la solución no es un único punto sino un conjunto (e.g. multi-objetivo), y cuando se busca/requiere paralelizar el cómputo.





Master/Slave es muy efectiva cuando alguna porción del proceso (el cómputo del fitness en general) es muy costosa.

Algoritmos Evolutivos

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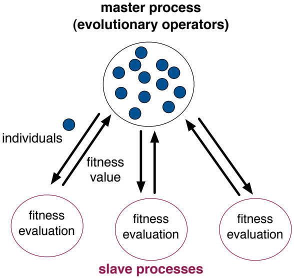
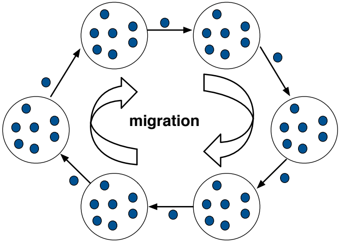
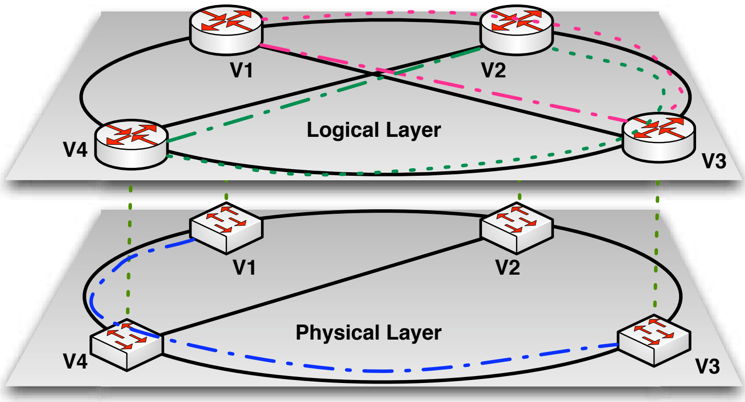




En *distributed subpopulations* se mantienen tribus o demes, cerradas a efectos de cruzamientos. Periódicamente se intercambian individuos mediante un operador de migración.

Solution representation

To represent individuals in Evolutionary Algorithms, two complementary sub-encodings were used:



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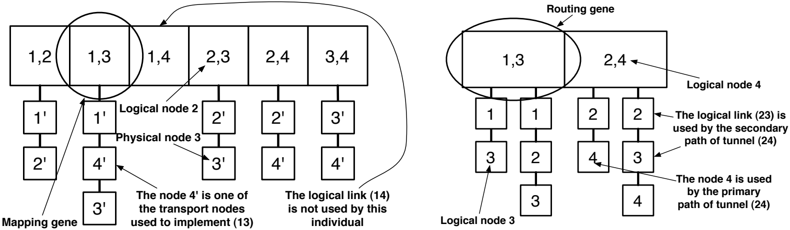


1. The mapping sub-encoding captures the configuration of lightpaths of an individual.
2. The routing sub-encoding represents active and standby paths for IP/MPLS tunnels.

Generating feasible solutions

The construction of an initial population is far from being easy.

Procedure createIndividual(V, L, P, $l : P \rightarrow \mathbb{R}_0^+$, $d : L \rightarrow \mathbb{R}_0^+$)**:**

$mapping\_genes \leftarrow \emptyset$, $routing\_genes \leftarrow sortDemands(V, L, d)$;
$k \leftarrow 0$, $N_{gen} \leftarrow |routing\_genes|$;
while $k < N_{gen}$ **do**
  $rgene \leftarrow routing\_genes[k]$, $k++$;
  if $incomplete(rgene)$ **then**
    $attempts\_num \leftarrow 0$;
    while $incomplete(rgene)$ and $(attempts\_num < max\_attempts)$ **do**
      $buildRoutingGene(rgene, V, L, P, l, d)$;
      $attempts\_num++$;
    if $incomplete(rgene)$ **then**
      $resetTaintedRoutingGene(routing\_genes)$;
      $k \leftarrow 0$;
return $(mapping\_genes, routing\_genes)$.

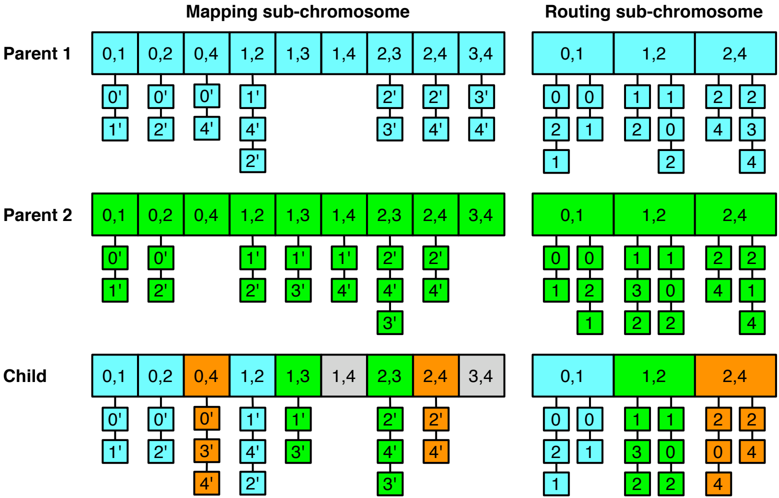
Generating feasible solutions

- The strategy consists in generating routing genes sequentially, taking demands in decreasing order of volume.
- Using a greedy randomized selection at each hop during the construction of primary and secondary paths, which are forced to be physically independent.
- During the construction of the routing genes, the creation of the mapping genes is indirectly triggered.
- This algorithm could lead to situations where paths cannot be built as a consequence of previous decisions.
- After trying *max_attempts*, those paths previously configured that blocked the way most of the times are reset.
- Their routing genes are erased, the list *routing_genes* is scanned again all along, and mapping genes only created because of paths of these routing genes are also reset.

Evolutionary Operators (Crossover)

- Se diseñó un operador específico (por el encoding).
- La descendencia se genera sorteando *routing genes*, de a uno en uno, entre los padres.
- Siempre que sea posible, se copian además los *mapping genes* dependientes de esos *routing genes*.
- El operador de *crossover* verifica la independencia física (la factibilidad del individuo).
- Si la inserción del *routing gene* fallara por falta de independencia, se intenta refactibilizar con el mismo *createIndividual*.

Evolutionary Operators (Crossover)



Evolutionary Operators (Mutation)

1. **data layer mutation** - It attempts to construct a new pair of primary/secondary paths preserving the mappings
2. **transport layer mutation** - It changes the mapping of lightpaths for some randomly selected mapping genes
3. **tabu link mutation** - It randomly selects a *tabu data link*, which is eliminated along with its associated genes
4. **best data layer mutation** - It is a local search operator that modifies the current solution 30 times (data layer mutation) while the best result is returned
5. **best transport layer mutation** - It is another local search operator that uses transport layer mutation 20 times

On all cases *createIndividual* is used to regain feasibility.

Complementary algorithms

- Besides the previously described algorithm, other metaheuristics were implemented using this EA as a skeleton.
- They are: Tabu Search (TS), a hybrid of EA and TS, and a Parallel Evolutionary Algorithm (PEA).
- The *distributed subpopulations* approach was chosen for the PEA, with 4 demes, 13 per-deme-individuals, and a per-deme-offspring size of 39.
- Only one individual from each deme is migrated synchronically, after three iterations.
- Whenever possible, all algorithms were used to find solutions for instances.
- Best solutions are kept for the result.

The problem of keeping routes

- Although the FRP problem is a relaxation of ASP, it is not easier at all.
- The only algorithm with which we found solutions for real-world instances was based on GRASP.
- An explicit routing encoding (like in EA) is impractical because of the great number of potential alternatives.
- Instead, we use a heuristic to determine the feasibility of constructions.
- Which embeds CSPF (Constrained Shortest Path First) in its core, a well-known polynomial-time algorithm.

Greedy Randomized Adaptive Search Procedure

Procedure GRASP(*ListSize*,*MaxIter*,*Seed*):

```
Read_Input_Instance();
for k = 1 to MaxIter do
    InitialSolution ← Construct_GRSol(ListSize, Seed);
    LocalSearchSolution ← Local_Search(InitialSolution);
    if cost(LocalSearchSolution) < cost(BestSolutionFound) then
        Update_Solution(BestSolutionFound, LocalSearchSolution);
    end
end
return BestSolutionFound;
```

GRASP es un framework para construir heurísticas.

Implementa un procedimiento iterativo que consta de dos fases.

Una construcción Greedy-Adaptativa-Randomizada.

Una Búsqueda Local para mejorar la anterior.

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Procedure Construct_GRSol(*ListSize*,*Seed*):

Solution $\leftarrow \emptyset$;
Incremental costs evaluation for the candidate elements;
while $\mathrm{not\_feasible}(\mathit{Solution})$ **do**
    RCL $\leftarrow$ the restricted candidate list;
    $s \leftarrow$ select randomly an element from the *RCL*;
    $\mathit{Solution} \leftarrow \mathit{Solution} \cup \{s\}$;
    Incremental costs revaluation;
end
return *Solution*;

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En cada iteración de *Construct_GRSol*, la RCL es recomputada buscando el menor incremento marginal (Greedy).

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En cada iteración de *Construct_GRSol*, la RCL es recomputada buscando el menor incremento marginal (Greedy).
También en cada iteración se suele recalcular los costos incrementales y se puede variar el tamaño de la lista (Adaptive).

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Entre ambos pasos se elige un nuevo componente al azar (Randomized), con alguna distribución que tenga relación con el costo marginal.

Greedy Randomized Adaptive Search Procedure

Procedure Local_Search(*Solution*):

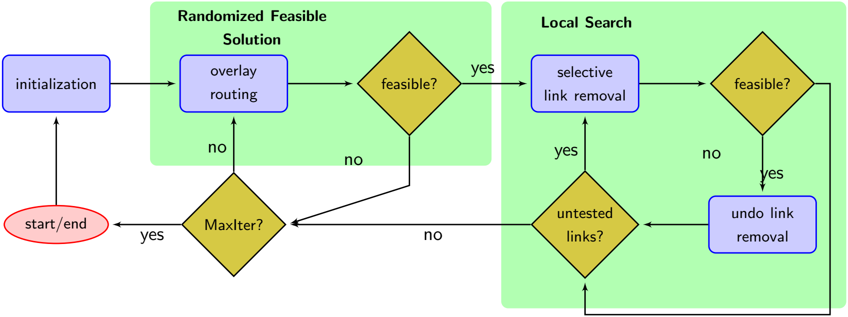
while not_locally_optimal(*Solution*) **do**
  Find $N\_Sol \in N(Solution)$ satisfying $f(N\_Sol) < f(Solution)$;
  $Solution \leftarrow Neigh\_Sol$;
end
return *Solution*;

There are two basic different strategies to explore a neighborhood:

best-improvement: all neighbors are investigated and the current solution is (possibly) replaced by the best neighbor.

first-improvement: when finding the first better neighbor solution (i.e. whose cost value is smaller than that of the current solution), the current solution is replaced by this one.

Block-diagram of our GRASP implementation



- The *Randomized Feasible Solution* creates a randomized mapping of lightpaths for a given set of logical links.
- The *Local Search* eliminates unnecessary links. A greedy first neighbor improvement is used.
- Because of its computational complexity, the feasibility is first checked before leaving the mapping construction.

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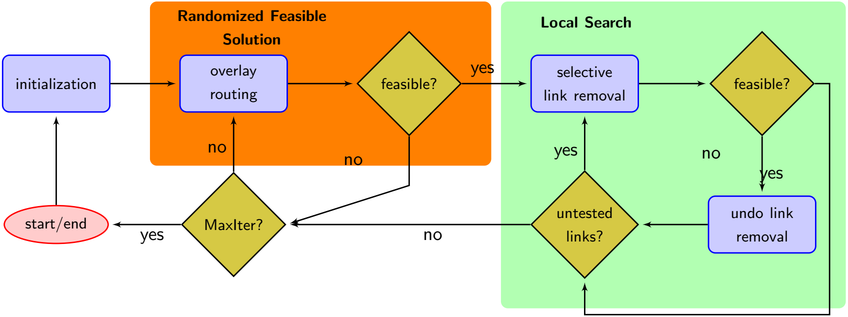

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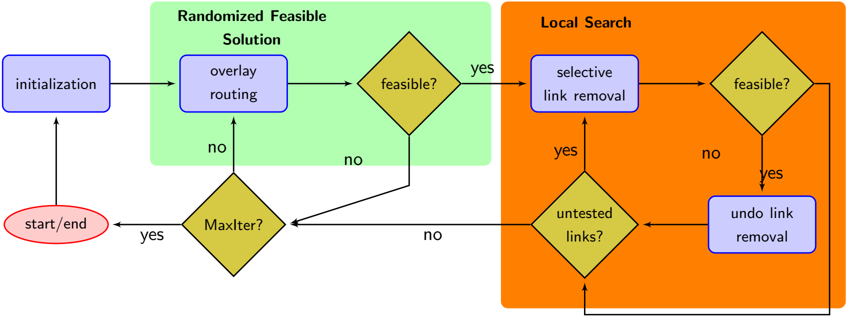

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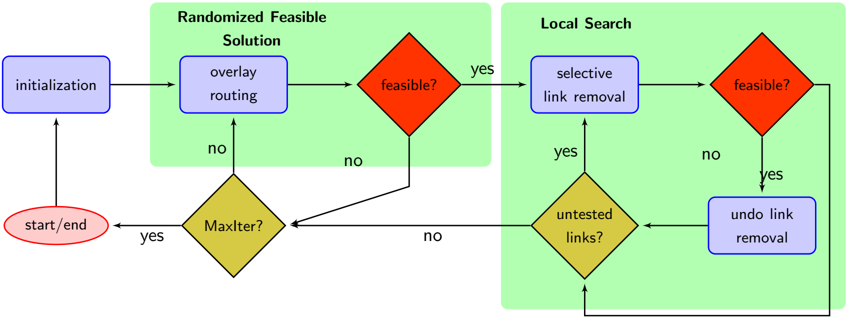

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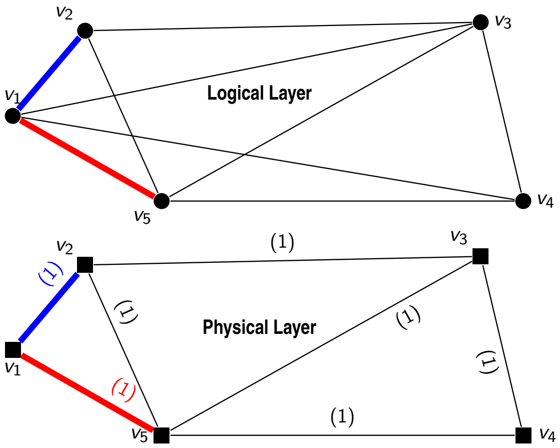
The mapping of lightpaths

Finding a physically independent mapping of minimum cost is an NP-Hard problem. We used a heuristic:

Procedure overlayRouting($(V,L),(V,P)$**,** $d : V \times V \to \mathbb{R}_0^+$**):**

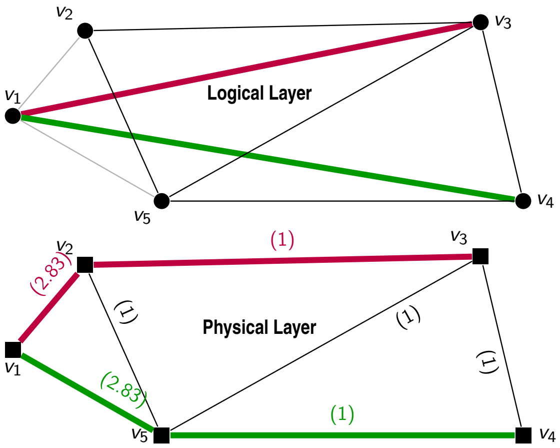
$sol(e) \leftarrow \emptyset$, $pd(e) \leftarrow 1$, $\forall e \in L$;
while exists $\text{not-processed}(v)$ **do**
  Select v randomly;
  $prob(vw) \leftarrow \frac{1}{d(v,w)}, \forall (vw) \in L \,/\, sol(vw) = \emptyset$;
  Normalize *prob* such that: $\sum_{e \in L} prob(e) = 1$;
  while exists $w \in V$ such that $((vw) \in L$ AND $sol(vw) = \emptyset)$ **do**
    Draw such $w \in V$ randomly weighted by $prob(vw)$;
    $shlp \leftarrow$ the shortest lightpath for (vw) without repeating physical links;
    if $(shlp = \emptyset)$ **then**
      $\mathrm{pd}(v,w) \leftarrow (1 + \sum_{e \in L} |sol(e) \cap \{(vw)\}|)^p$ for all $(vw) \in P$;
      Restart *repeated physical links control window*;
    else
      $sol \leftarrow sol \cup \{shlp\}$;
return $sol : L \to 2^P$.

The mapping of lightpaths



The mapping chosen for: (12), (15), (13), (14), (23) and (35).

The mapping of lightpaths



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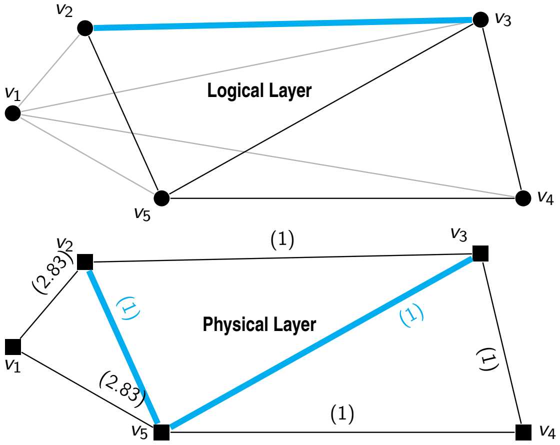

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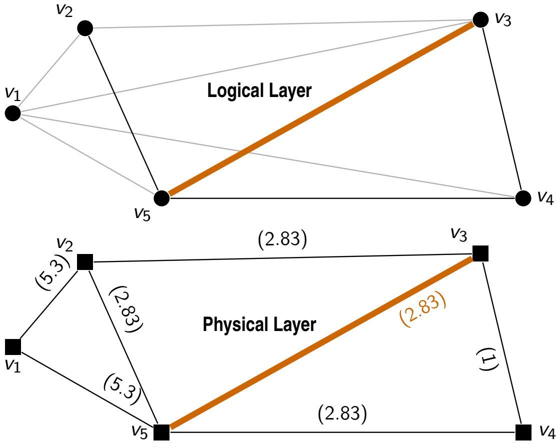

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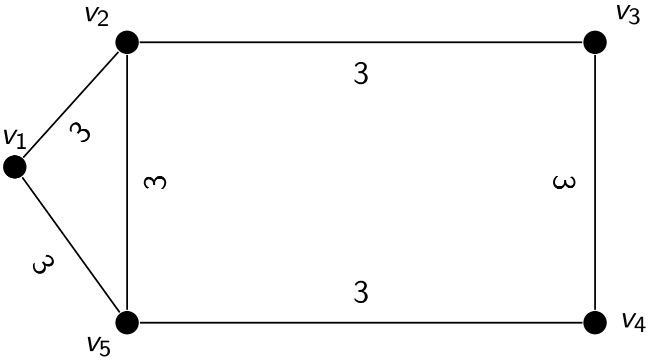
Checking feasibility

Univocally determining the feasibility of a construction is also NP-Hard. We generalized an NPP heuristic to develop another:



A routing configuration for $d_{24} = 2$, $d_{12} = 1$, $d_{13} = 1$ and $d_{23} = 1$.

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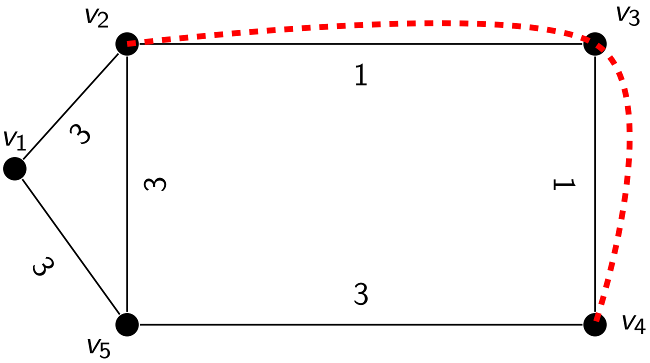

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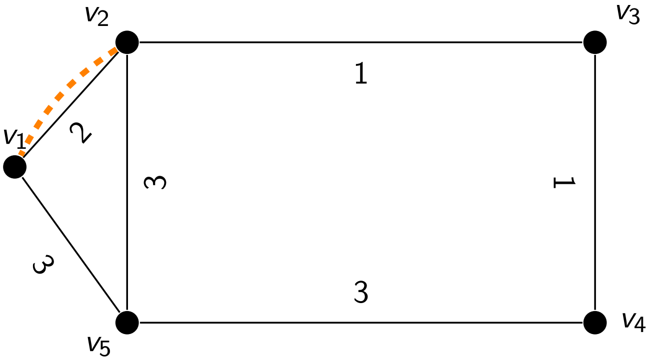

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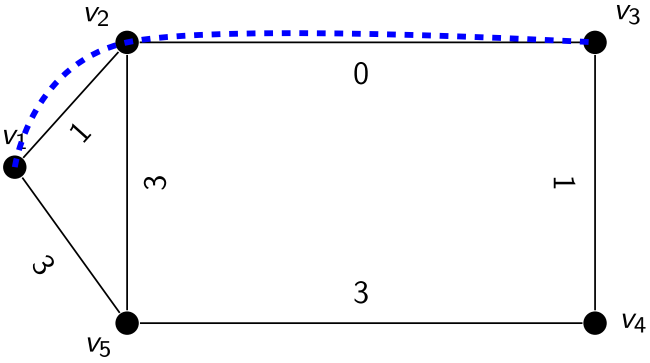

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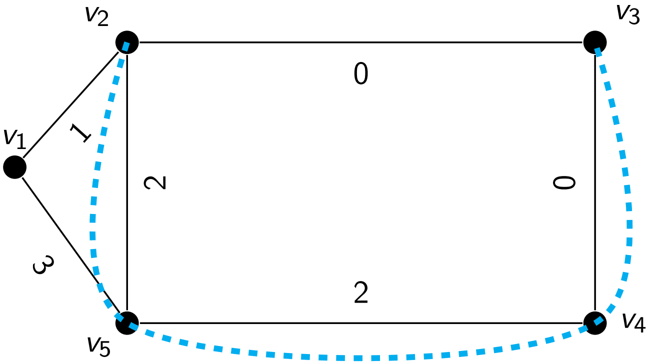


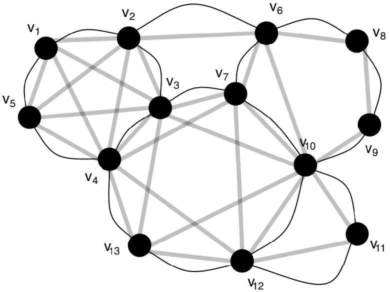
A routing configuration for $d_{24} = 2$, $d_{12} = 1$, $d_{13} = 1$ and $d_{23} = 1$.

Checking feasibility

- Given a particular mapping, this algorithm must be run as many times as physical fault scenarios to check feasibility.
- Thus, the *isFeasible* function is the most expensive subroutine in term of computational cost.
- Besides it must be used many times during the *local search*.
- That is why we used the first neighbor approach.
- Fortunately, most of the routes amid fault-scenarios are reusable.
- And caching paths reduces computations notoriously.
- This heuristic might cast false negatives.
- Demands order and control window aside, the core of this heuristic is replicable by a standard CSPF.

Controlling the candidate list

In order to avoid an unstable behavior we put effort to reduce the number of potential logical links within the input data-set.



To dimension the capacity within internal faces we used some exact solutions.

Complementarily, the bonds condition added capacity through links between faces.

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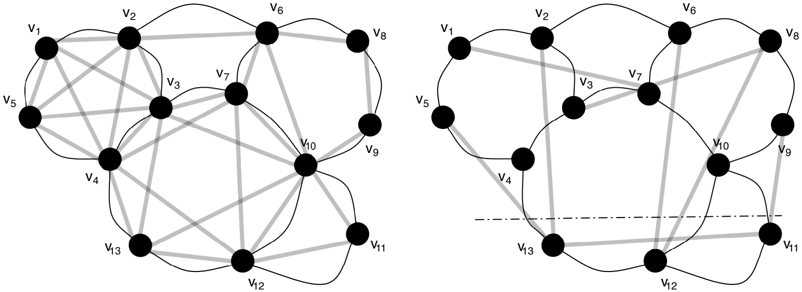

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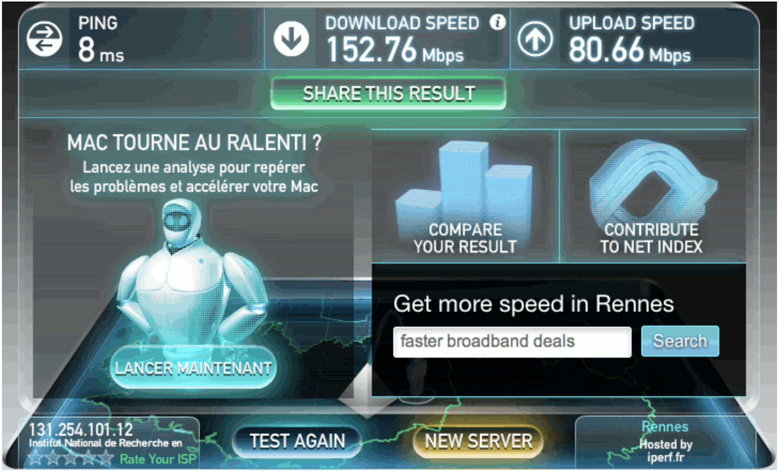
The RAU (Universitary Academic Network)

- Academic networks are an essential asset for universities.
- With different goals to those of commercial Internet.
- The RAU constituted the first point of Internet in Uruguay.
- And it still is the backbone of uruguayan academic institutes.
- On 2003, the RAU was connected to other regional (CLARA) and European academic networks (ALICE).
- These connections were supported over an ATM overlay.
- With them, the last redesign of the network took place.
- Today, the RAU brings services to professors, researchers and administrative staffs of some faculties.
- Students have no access to RAU's services in general.
- Today, RAU's switching capacity is thousands of times lower than North American or European counterparts.

The current performance of RAU



A desktop terminal at France (INRIA-Rennes).

The current performance of RAU

The same terminal in Uruguay (FING).

The current performance of RAU

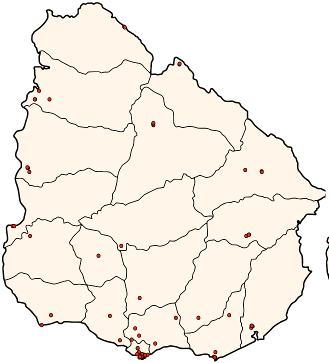
The bandwidth must be increased, but what about the users?

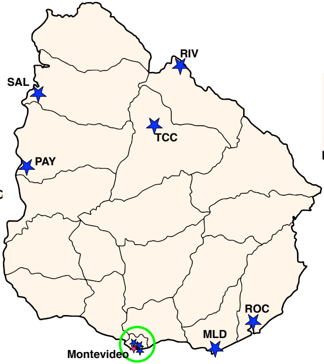
A new universe of users

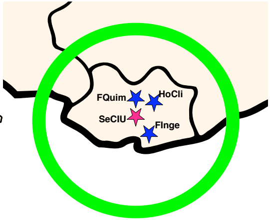
- The new RAU is planned to reach everyone:
  1. 11,000 professors and researchers.
  2. 7,000 administrative employees.
  3. 140,000 students.
- Increasing the effective bandwidth to:
  1. 100Mbps for employees (UTP).
  2. 10Mbps for regular students (WiFi).
- Bringing world-class performance for researches and students.
- Supporting the development of new applications and protocols.
- Potentiating inter-institutional applications.

An evolutionary leap for RAU

Since some years ago SeCIU and ANTEL are working to redesign the RAU in order to span 108 points, 60 of them in Montevideo. The backbone of this new network counts 10 POPs and nodes.







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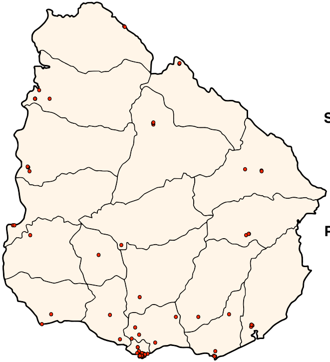

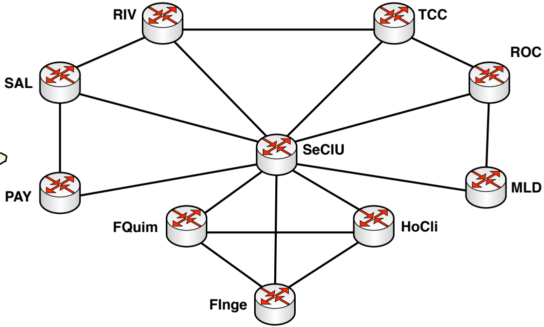

Some budgets

- The current annual budget of RAU is of USD 1,283,500 and it has the following composition:
  1. Internet Alianza (200Mbps) USD 450,000.
  2. Connection to Clara (STM-1) USD 260,000.
  3. Local connectivity for RAU USD 573,500.
- The initial project for RAU2 doesn't change the scheme of external connections (Internet, Clara).
- It substitutes the internal connectivity, with an annual budget of USD 1,006,500, on a 10 years project.
- Relative weights for access and backbone are:
  1. 84 % Backbone
  2. 16 % Access (8% new OF + 8% optical transport)
- We used the prices included in this project (also new Internet prices) as input cost to redesign the network.

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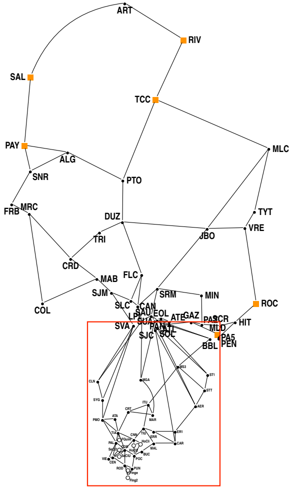
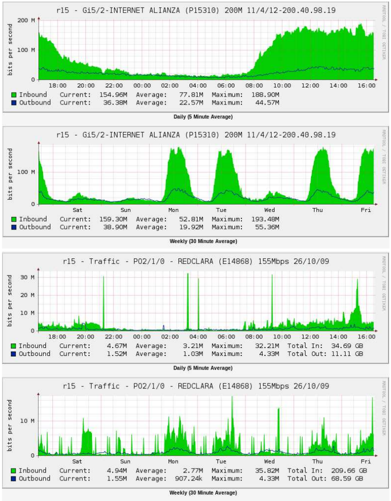
Physical network



RAU's traffic (2013)



Design premisses

- An important amount of effort consisted in monitoring current traffic between points.
- Based on it, we projected the future traffic of the network.
- We agreed with SeCIU two traffic forecast as extreme cases: 35 (low) and 206 (high) times higher than current.
- The physical network used, is the result of overlapping ANTEL's and other optical networks.
- Besides of its immediate application, this design was also used to assess the viability of deploying an open-source based backbone.

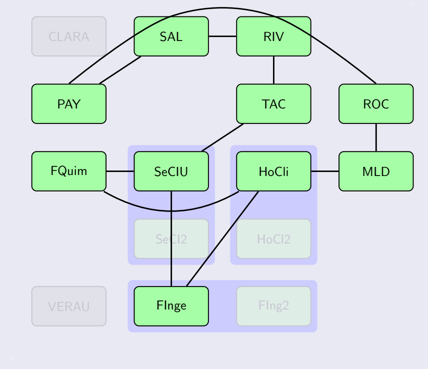
Scenarios modeled

We analyzed and modeled several variants for the network, which were synthesized as MORNDP instances.

scenario index	*demand type*	*classes of traffic*	*nodes considered*	*border routers*	*additional comments*
AL	low	Internet	originals	SeCIU	baseline configuration
AH	high	Internet	originals	SeCIU	baseline configuration
01	low	Internet	originals	SeCIU	data-set tuning
02	high	Internet	double node at HoCli	SeCIU	data-set tuning
03	low	on-line	double nodes at: SeCIU, HoCli and FIng	SeCIU	extra nodes improve the quality of constructions
04	high	on-line	double nodes at: SeCIU, HoCli and FIng	SeCIU	extra nodes improve the quality of constructions
05	low	on-line	same double nodes plus VERAU and CLARA	Backbone	simulates a change of the peering scheme
06	high	on-line	same double nodes plus VERAU and CLARA	Backbone	simulates a change of the peering scheme
07	low	on-line	originals	Points	gets Internet off the RAU
08	high	on-line	double node at HoCli	Points	gets Internet off the RAU

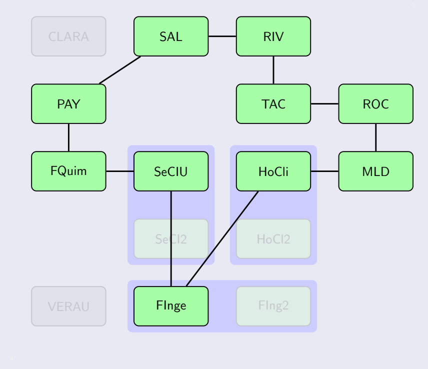
Best solutions for scenario 1

ASP-MORNDP



BB's total length: 3,022km.

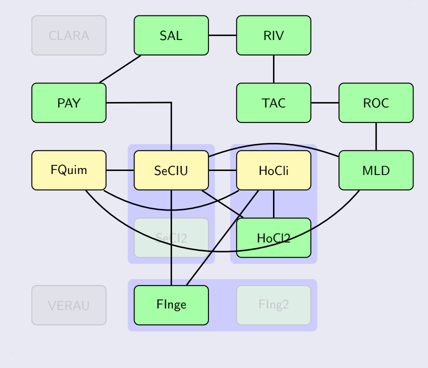
FRP-MORNDP



BB's total length: 2,939km.

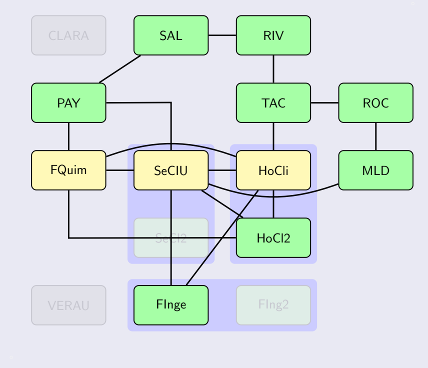
Best solutions for scenario 2

ASP-MORNDP



BB's total length: 3,799km.

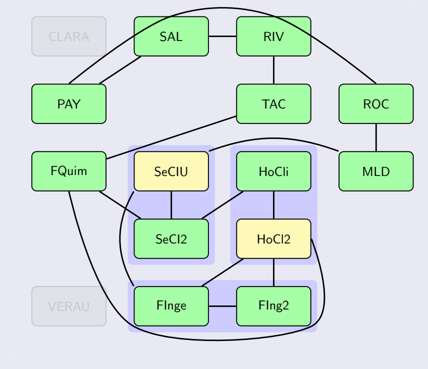
FRP-MORNDP



BB's total length: 4,976km.

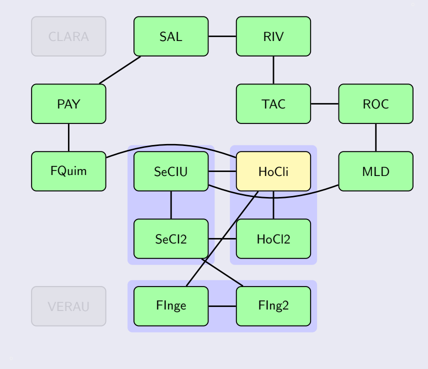
Best solutions for scenario 3

ASP-MORNDP



BB's total length: 3,536km.

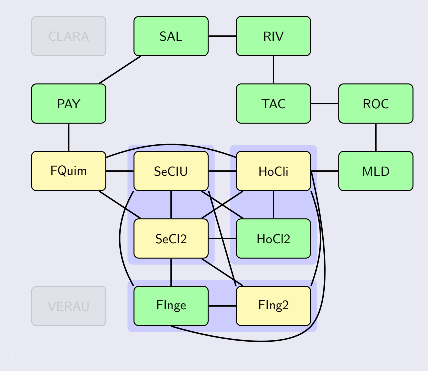
FRP-MORNDP



BB's total length: 3,250km.

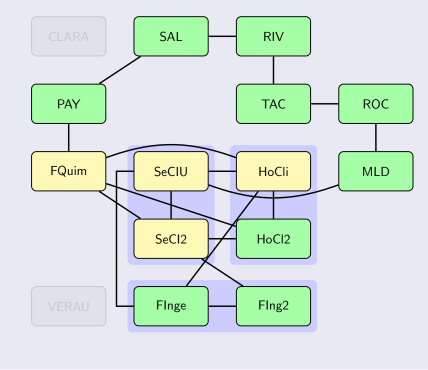
Best solutions for scenario 4

ASP-MORNDP



BB's total length: 3,978km.

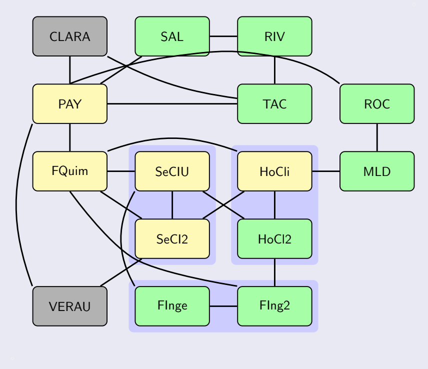
FRP-MORNDP



BB's total length: 3,585km.

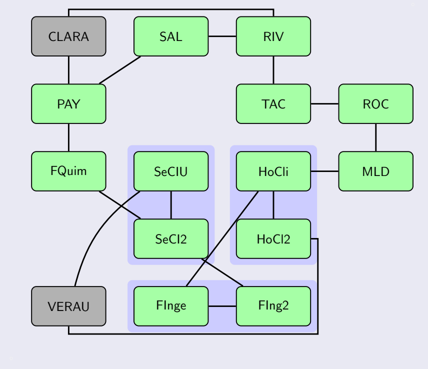
Best solutions for scenario 5

ASP-MORNDP



BB's total length: 6,488km
Refined total length: 5,893km.

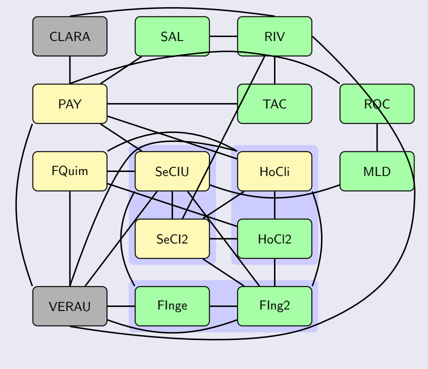
FRP-MORNDP



BB's total length: 5,498km
Refined total length: 3,022km.

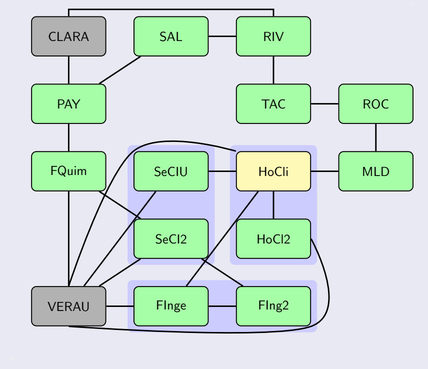
Best solutions for scenario 6

ASP-MORNDP



BB's total length: 10,888km
Refined total length: 4,177km.

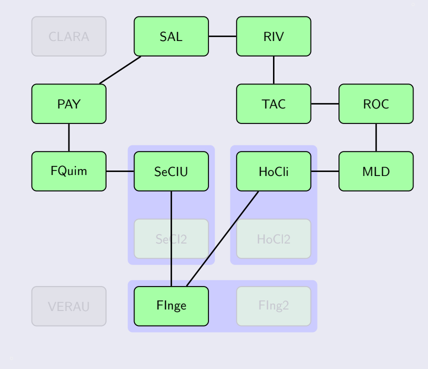
FRP-MORNDP



BB's total length: 8,945km
Refined total length: 3,081km.

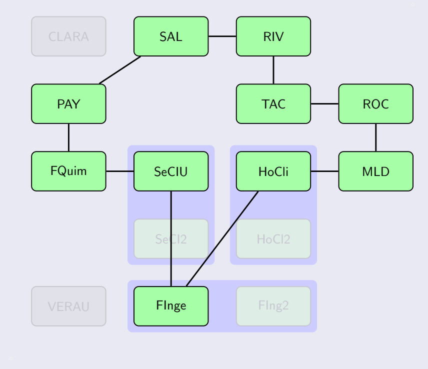
Best solutions for scenario 7

ASP-MORNDP



BB's total length: 2,939km.

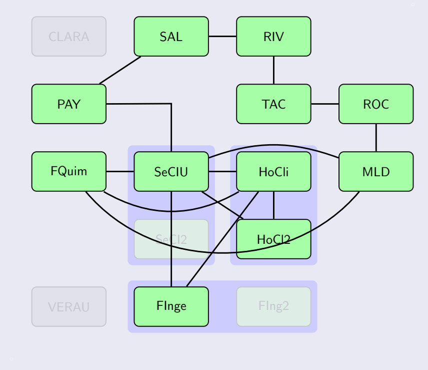
FRP-MORNDP



BB's total length: 2,939km.

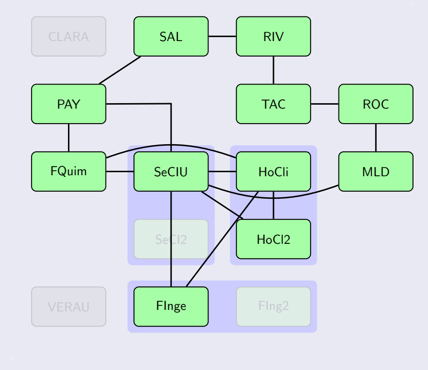
Best solutions for scenario 8

ASP-MORNDP



BB's total length: 3,799km.

FRP-MORNDP



BB's total length: 3,126km.

Cost analysis for models and algorithms

scenario index	*backbone cost ASP*	*& FRP*	*VERAU cost ASP*	*& FRP*	*CLARA cost ASP*	*& FRP*	*annual cost ASP*	*& FRP*
01	416,613	405,171	163,988	163,988	34,851	34,851	615,452	604,010
02	523,730	685,991	961,323	961,323	205,122	205,122	1,690,175	1,852,436
03	487,473	448,045	163,988	163,988	34,851	34,851	686,312	646,884
04	548,407	494,228	961,323	961,323	205,122	205,122	1,714,852	1,660,673
05	812,409	416,613	163,988	163,988	13,035	11,313	989,432	591,914
06	575,841	424,747	672,926	576,794	76,720	66,585	1,325,487	1,068,1 26
07	405,171	405,171	369,277	369,277	34,851	34,851	809,299	809,299
08	523,730	430,950	893,271	893,271	205,122	205,122	1,622,123	1,529,343

- FRP/GRASP found the lowest cost solutions for all scenarios but one (02).
- The exception is due to instabilities in the lightpaths mapping, avoided after increasing the number of nodes.
- Cheapest subcomponents do not match among scenarios.

Cost analysis for scenarios

scenario	*Level of demand*			*Annual cost (USD)*				
index	*Internet*	*Clara*	*Internal*	*Access*	*Backbone*	*VERAU*	*Clara*	*Total*
AL	7,022	-	-	161,040	845,460	163,988	34,851	1,205,339
AH	41,164	-	-	161,040	845,460	961,323	205,122	2,172,945
01	7,022	-	-	86,490	405,171	163,988	34,851	690,500
02	41,164	-	-	86,490	523,730	961,323	205,122	1,776,665
03	7,022	1,050	412	86,490	448,045	163,988	34,851	733,374
04	41,164	6,180	2,425	86,490	494,228	961,323	205,122	1,747,163
05	7,022	1,050	412	86,490	416,613	163,988	11,313	678,404
06	41,164	6,180	2,425	86,490	424,747	576,794	66,585	1,154,616
07	7,022	1,050	412	86,490	405,171	369,277	34,851	895,789
08	41,164	6,180	2,425	86,490	430,950	893,271	205,122	1,615,833

- The original design is not feasible for high demand.
- For a given level of demand, the lowest cost is achieved for those scenarios where the traffic is distributed (05 y 06).
- For low-demand, the spread is 78% (USD 526,935) and the cost would be 53% of the current (USD 1,283,500).
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Main conclusions for RAU's application

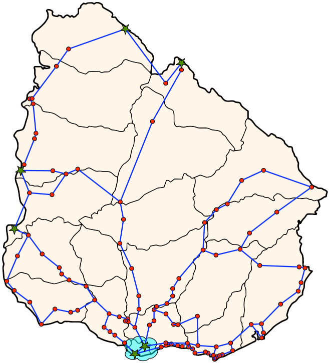
- An update of technologies and costs, combined with a proper network design, would allow us to deploy a 200 faster RAU2 keeping the budget.
- Contrary to what was supposed, getting Internet traffic off the RAU rises the costs.
- Bandwidth requirements for all scenarios are theoretically supported with open-source routers.
- Although the natural core for this backbone includes SeCIU, it must span other POPs (Fing, HoCli).

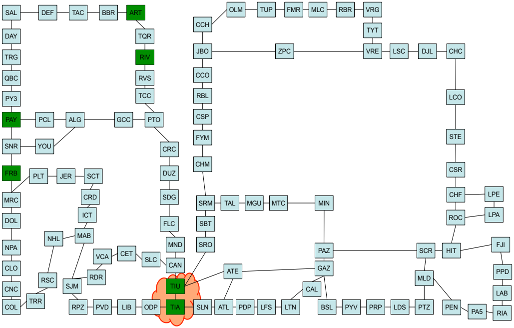
The backbone of ANTEL

- ANTEL is the Uruguayan government-owned telecommunications company. It holds:
  1. 100% (over 1 million) of the fixed telephony lines.
  2. 48% of the 5.13 million mobile phone services.
  3. Around 95% of the 653.000 broadband Internet access connections.
- Concentrates over 70% (USD 860 million) of the total incomes of non-broadcast telecommunications services.
- It is the most important ISP of Uruguay.
- By the late 2000's, ANTEL was on its way to substitute legacy ATM and pure IP technologies by IP/MPLS.
- The deployment of the metropolitan portion took place earlier.
- We collaborated with the rest of the network.

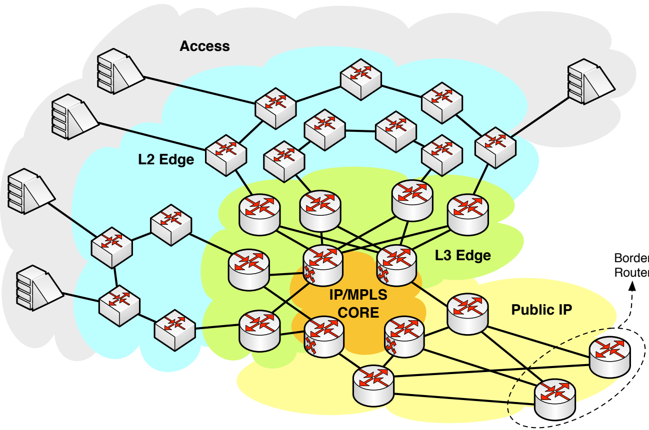
Topology of optical layer

ANTEL's optical network was designed for the telephone service and its purpose was to connect all points towards Montevideo.





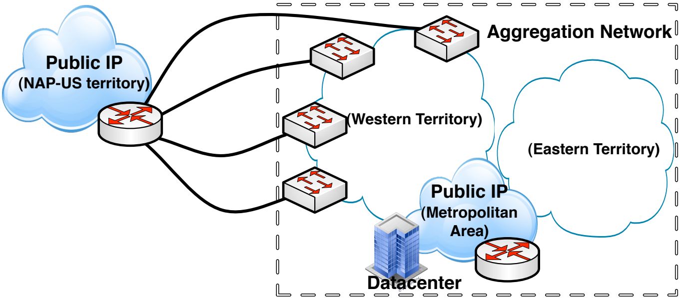
Structure of the logical layer



The logical layer has a structure of functional components.

Geographical correspondence

Most of the network infrastructure is placed within Uruguay.



The public IP network has presence at Miami and it is transparently connected through SDH links.

Scenarios modeled

As we did for RAU, this application considered many scenarios which were expressed as instances of MORNDP.

scenario index	*traffic scenario*	*local content*	*merged networks*	*Internet demand*	*international demand*	*total demand*
01	Low	H	N	40,412	30,309	53,462
02	Low	H	Y	40,412	30,309	53,462
03	Low	L	N	40,412	40,412	53,462
04	Low	L	Y	40,412	40,412	53,462
05	Medium	H	N	45,243	33,932	58,293
06	Medium	H	Y	45,243	33,932	58,293
07	Medium	L	N	45,243	45,243	58,293
08	Medium	L	Y	45,243	45,243	58,293
09	High	H	N	79,159	59,369	92,209
10	High	H	Y	79,159	59,369	92,209
11	High	L	N	79,159	79,159	92,209
12	High	L	Y	79,159	79,159	92,209

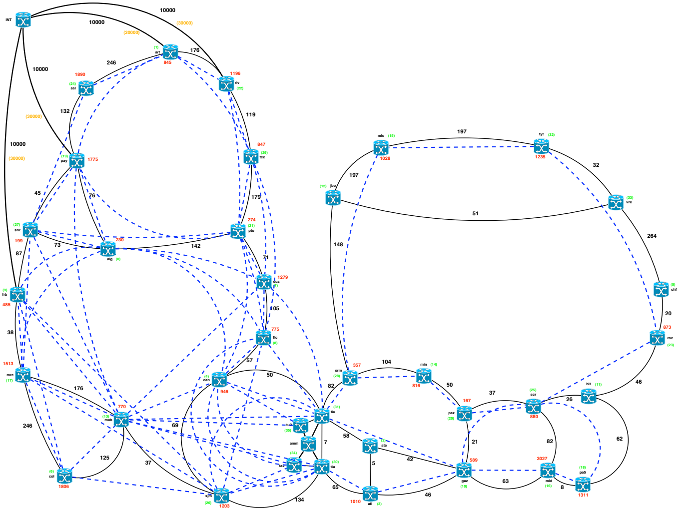
Virtual nodes are included to reflect design premisses (34/68).

Best referential results for scenarios

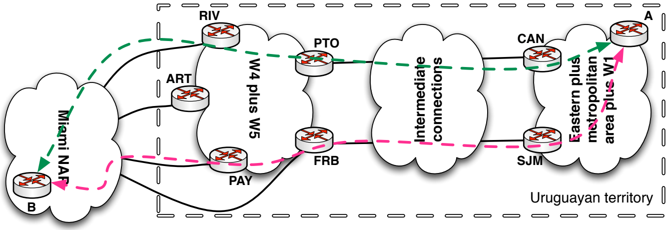
scenario index	*Internet cost*	*backbone cost ASP*	*& FRP*	*international cost ASP*	*& FRP*	*total cost ASP*	*& FRP*
01	916	287	265	3,716	3,716	4,919	4,897
02	916	700	369	2,554	2,554	4,170	3,839
03	1,198	287	265	4,645	4,645	6,130	6,108
04	1,198	559	419	3,406	2,980	5,163	4,597
05	987	277	265	3,716	3,716	4,980	4,968
06	987	723	383	2,980	2,554	4,690	3,924
07	1,339	277	265	4,645	4,645	6,261	6,249
08	1,339	573	484	3,832	2,980	5,744	4,803
09	1,691	311	313	5,574	5,574	7,576	7,578
10	1,691	740	617	5,109	3,406	7,540	5,714
11	2,255	311	313	7,432	7,432	9,998	10,000
12	2,255	846	725	6,386	4,683	9,487	7,663

- FRP/GRASP found the lowest cost solutions for all scenarios but two (09 and 11, spread 0.25%).
- At the same demand volume, best solutions were always found with FRP/GRASP (spread 32%).

What explains this spread?

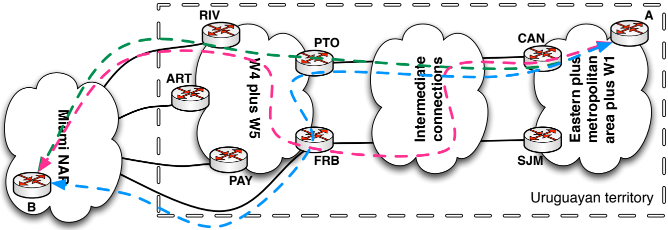


What explains this spread?



- ASP-MORNDP must allocate two end-to-end physically independent paths.
- In general ASP-MORNDP supports 1:N protection (because of the shared spare capacity).
- However, for this physical network ASP cannot exploit it when paths cross the intermediate zone.

What explains this spread?



- Conversely, FRP-MORNDP can implement a different protection for each potential fault.
- Hence, can reuse spare capacity of international (most expensive) links.
- These savings explain the gap between models.

Main conclusions for ANTEL's application

- Important cost savings (above 30%) may come from merging aggregation and public IP networks.
- The current core is historically placed at Montevideo.
- The optimal core for ANTEL's network should span some interior departments.
- With such a core, similar savings may be achieved by placing routers over the national and abandoning SDH protections.
- Which also contributes to reduce costs by suppressing an intermediate overlay.

Conclusions and future work

- The environment into which physical networks were designed has changed dramatically, turning inconvenient important portions of these networks, and obsolete many legacy practices.
- IP/MPLS supports the convergence of all kinds of services upon a single and highly resilient logical layer.
- However computationally hard problems, which coordinate logical and physical levels are necessary to guarantee resiliency.
- In this work, we presented two versions of such models and meta heuristics to find solutions to real-world instances.
- Both models proved to be very suitable to adapt to a diverse set of design alternatives, while results allow reducing costs up to 50% with respect to manually designed constructions.
- Saving are even more important when we consider that an entire overlay can be suppressed.

Conclusions and future work

- The FRP model substantially increases the quality of the solutions for some instances.
- These improvements would have passed unnoticed for ASP, and also for other multioverlay models reviewed.
- Thus, giving this freedom to the tunnels construction in the model was a good decision.
- Regarding the lightpaths, the results show that physical paths in solutions are not far from expected (low cost and mostly independent paths).
- With cards seen, we should conclude that this level of complexity is not profitable.
- If we had to redo this work, we would put more emphasis in determining the proper combination of logical links, rather than determining lightpaths for them.

Conclusions and future work

- As expected, all solutions found for ASP are plenty practical/realizable on most combinations of providers.
- Additionally, the analysis of solutions shows that most of them also are practical when the main path is strictly provisioned.
- Furthermore, for those who are not, a minimal logical over-engineering also fixates the bumping issue.
- So the results of these algorithms are not only based on real-world instances, but also constitute real-world solutions, which perhaps is the most important result.

Published articles

- A Parallel Evolutionary Algorithm for Multilayered Robust Network Design. In 3PGCIC-12. Victoria, BC, Canada, November 2012.
- Optimal design of a multi-layer network. An IP/MPLS over DWDM application case. InTech: Current Developments in Optical Fiber Technology. June 2013.
- Using metaheuristics for planning resilient and cost-effective multilayer networks. In RNDM-13. Almaty, Kazakhstan, September 2013.
- Using GRASP for designing a layered network: A real IP/MPLS over DWDM application case. International Journal of Metaheuristics, December 2013.
- Optimal design of an IP/MPLS over DWDM network. Pesquisa Operacional - Special Issue from CLAIO/SBPO 2012, May 2014.