Traffic Grooming, Routing and Wavelength Assignment in Metropolitan Transport Networks

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Abstract— The Optical Transport Network’s delivery on the promise to supply high bandwidth availability, OAM&P support, accommodation of multiple client signals and efficient capacity utilization when in combination with WDM’s technology has stirred service providers’ attention. The winning argument comes in the form of the OTN switch, a device that can be integrated with the evolved WDM ROADMs to provide for lambda and sub-lambda switching in accomplishment of high bandwidth efficiency. The current work features the optimized planning of OTN/WDM networks as a means to minimize the acquisition costs and to maintain the profit margins by driving down the cost per transported bit as the demanded traffic volume increases. The featured planning techniques encompass the problem of traffic grooming onto optical channels to minimize the equipment related costs as well as the routing and wavelength assignment problem to comply with the restriction that the number of wavelengths per fiber cannot be exceeded. All expenditures are traced back to the deployment of optical line cards. Both mathematical programming ILP models as well as a heuristic are presented. Different node architectures are taken upon consideration to make for the cases of opaque, transparent and translucent networks. Mixed and single line rate network scenarios are attended and put to comparison to assess on their performance in achievement of the lowest expenditures.

Index Terms— OTN/WDM, grooming, ILP, heuristic, cost

I. INTRODUCTION

The past years in the telecommunications landscape were rich in evolution, in increased, diverse and enticing new offers and in user’s behavioral changes. As the IP world became the powerhouse for the growth of a multitude of new applications, data-traffic escalated at an elevated rhythm, multiplying year over year. Simultaneously, revenue income became withheld mostly by the applications’ owners. The rising traffic volumes and services’ convergence on the IP backbone put new strains upon the access and metropolitan domains, consequently extending to the core network that had to support these flows of aggregated traffic. As the revenue associated with IP services does not walk on par with the pace in which traffic growths, the revenue per transported bit decreases creating struggles for operators that have to search for new ways to create value. To make matters worse, requirements moved from best effort to more strict ones concerning high bandwidth and availability, low latency, jitter and elevated QoS. The breakthroughs in optical technologies that culminated with the introduction of 100 Gbps transponders and the envisioning towards 400 Gbps agitated discussion regarding the evolution of the transport network.

These rates far exceed the scalability of the SONET/SDH network and in lieu of the absence of a sub-wavelength layer routers must be directly connected to the wavelength layer at raw wavelength capacity. The heavy and increasing volumes of traffic put new burdens on routers that have to be upgraded in terms of number of ports, size and processing capacity. Together with higher power consumption, these factors skyrocket costs. As studies reveal that most of the processing capacity of routers is dedicated for in transit traffic, new solutions that combine optical transport and sub-wavelength routing are being pursued. The idea is transporting IP traffic at a most economical underlay layer, capable of managing flows between different locations optimally ensuring connectivity to the IP backbone infrastructure. Opened the window of opportunity to rethink the transport network, the new data centric driven architecture must be aligned with the intent to solve the cost-capacity problem and mostly, to minimize the total cost of ownership. To inherit the legacy of SONET/SDH networks, it is also demanded for enhanced flexibility to deal with changes in traffic patterns, backwards compatibility to accommodate the always relevant synchronous signals and for high availability and robustness, giving continuity and magnifying the OAM&P features operators were accustomed to. OTN stands as a qualified solution by permitting the convergence of multiple services onto one same platform, a single management entity in place. Alongside the automation of network functionality, the prospect of OpEx cut backs is offered. The ability for lambda and sub lambda switching via integration of OTN switches with WDM network components in turn aids to increase capacity utilization and the sharing of the costs of transport over a larger number of signals, driving down the cost per transported bit. The problem of scaling the IP network is attended by delegating the switching functionality to the OTN network, taking in the increased traffic demand without inducing the extra costs associated with routers capacity upgrades.

Never dissociated from such network evolutions and migration processes is the need for new equipment to be deployed, the incurrence in capital expenditures mandatory. Over the course of this work, the issue of minimizing the acquisition costs is attended in the scope of OTN/WDM networks with the development of GRWA algorithms to minimize the number of required line cards to satisfy the whole of the traffic demand. These are assumed to be the costlier component accounting for a network’s capital expenditures and all other factors are despised. OTN switches are assumed to have unlimited grooming capacity and the fiber optical impairments causing degradation of the light pulses are neglected. For an approach on traffic grooming and
regenerator placement methodologies concerning the cost minimization problem, the reader is remitted to [1]. Translucent, transparent and opaque network configurations are brought under comparison to determine which can be deployed with the lowest associated capital expenditures.

Telecommunication networks are becoming increasingly heterogeneous, supporting a wide range of client protocols, experiencing traffic pattern variations and imbalanced traffic loads among distinct source-destination pairs. In such a diverse scenario, a mixed line rate approach may prove more fit, the ability of a fiber link to support multiple line rates, each in a non-overlapping wavelength, allowing for an enhanced management of the traffic flows and necessary resources. On that note, high bandwidth services can be carried directly over wavelength channels while the grooming of lower rate signals can be planned according to the availability of high order OUDs in achievement of the highest bandwidth efficiency. In allowing for the coexistence of mixed line rates in a single fiber, cost dissimilarity ensues as transmitter equipment associated with higher bandwidth signals comes at a higher expense. As so, the selected rates of the deployed optical channels become another factor weighing in on the total network’s cost. In [2], the authors present an integer linear programming formulation for impairment aware optical networks with mixed line rates. The intention is to minimize the network’s cost by conducting routing, wavelength and rate assignment, balancing the despair line card’s costs, bandwidth and optical reach in accordance to the pattern and amount of traffic that must be served. Expenditures are traced back to the deployment of transponders. Results attained comparing single and mixed line rate networks with an availability of 10, 40 and 100 Gbps lightpaths pended in favor of the superior cost effectiveness of the multi rate scenario. A distinct approach is taken in [3], with the presentation of a heuristic formulation with a primary goal of minimizing network’s cost and a secondary one to minimize the wavelength cost perceived as the average number of assigned wavelengths per link. Network related expenditures are associated solely to the optical line cards cost. Contrarily to the previously mentioned work, the authors despise the signal degradation that comes with transmission over optical fibers. Though different assumptions are made, the results comparing single and multi-rate networks with 10 and 100 Gbps optical channels available converge to the same conclusion that the multiple rate scenario is an enabler for lower costs.

In the next sections, integer linear programming formulations as well as a heuristic are presented with the purpose to minimize the network’s cost assuming lightpaths of distinct rates can be established. Opaque, translucent and transparent node configurations are accounted for in the formulations as well as single and mixed line rate network schemes. The work is organized as follows: section II presents the general cost minimization problem statement outlining the assumptions made. Section III regards the considered network node’s architecture necessary to design the opaque, transparent and translucent configurations targeted by the formulations. Section IV presents the Ip models for the cost minimization challenge and the following one presents an overview of the developed heuristic. Section V culminates with the showcase of attained results applying the mathematical and heuristic models and with the conclusions regarding the quality of these last ones. In the end, the heuristic is applied to a real life network.

II. PROBLEM DEFINITION

The current work features the cost minimization problem. Assuming traffic grooming an enabler for lower capital expenditures, the problem tackled is that of minimizing the number of optical line cards to satisfy a static traffic demand. These are considered the solemn accountable for network costs. The goal is to aggregate client signals that by themselves claim only a portion of the optical channels’ bandwidth in order to pack wavelengths as efficiently as possible so that fewer resources can be deployed. Client signals can be groomed onto optical channels as long as their capacity is not exceeded. It is assumed that all network nodes are equipped with both electrical as well as photonic switching fabrics. Intermediate grooming and optical bypassing are therefore allowed. The routing and wavelength assignment of the optical channels must comply with the clash constraint in that no two channels can be assigned the same wavelength in the same fiber link. No wavelength converters are present making it so that the wavelength continuity constraint is in place.

The line cards are equipped with a transponder and an OTN mux/demux. Though muxponder solutions could be utilized, the choice over this approach lays on the higher flexibility of multiplexing options and on the fact that no restrictions are place on the service’s signals, the only constraint being the limit imposed by the optical channels’ bandwidth.

A set of client signal data rates is considered (1.25, 2.5 and 10 Gbps) and it is assumed distinct line rates (40 and 100 Gbps) can coexist in the same fiber. The costs of the line cards are normalized to that of the card corresponding to the lowest line rate allowed in the network. To perform a more extent analysis three cost ratios are considered taking values of 1.5, 2 and 2.5.

III. NODE ARCHITECTURES CONSIDERED

As a means to explore different perspectives on the traffic grooming problem, a set of network configurations was considered. By selecting distinct types of equipment to be deployed at each network node, opaque, transparent and translucent configurations were attained as follows:

Translucent: This is the most flexible approach but one that involves that some or all network nodes are equipped with both optical as well as electrical switching fabrics. The client cards insert/collect streams from a variety of services and protocols into/from OTN frames. At the ODU switch, locally added signals are routed alongside in-transit demultiplexed signals from terminated wavelengths onto the line cards’ ports. Incoming signals from the DWDM network also surpass the ODU switch to be delivered to the rightful client cards. The line cards, as detailed in the figure, are composed of OTN Multiplexer/Demultiplexers and of Optical Transponders. These devices multiplex the groomed signals
from the ODU switch and convert the composite signal to the optical domain and, in the reverse direction, convert the optical signal into the electric domain and further demultiplex the carried ODU signals. At last, the multi-degree ROADM not only allows for wavelength channels to be added or dropped but also performs optical bypassing by switching wavelengths from incoming to outgoing fibers. By optimally combining wavelength and sub-wavelength electrical switching by means of ROADMs and ODU switches, either as a multi-granular integrated device or as standalone solutions connected by short reach interfaces, traffic grooming can be complemented with optical bypassing to drive down the cost per transported bit. One could have, for instance, close to completely or completely filled 100 Gbps optical channels bypassing all intermediate nodes on path to destination and poorly filled 100 Gbps optical channels terminated at intermediate nodes and aggregated onto a better filled outgoing wavelength with locally collected traffic sharing a common path.

**Transparent:** Signal switching is restricted to the optical domain. Locally added streams are mapped onto OTN frames at the client cards. These cards are connected to line cards that convert the electrical signal to the optical domain. The resulting wavelengths surpass the ROADM that performs the switching required to route them towards the appropriate fiber ports. Client streams are carried in a single direct lightpath from source to destination as intermediate nodes are always optically bypassed. On the matter of line cards, Figure 2.10 displays three possible configurations: one composed of an ODU multiplexer/demultiplexer and of a transponder, a configuration featuring a muxponder device and yet another approach with a single transponder. While the first two configurations have the ability to multiplex sub-rate streams onto a higher bandwidth signal that is later converted to the optical domain, the static muxponder solution generally restricts the client side signals to only a subset of the possible service rates (for instance, 10x10 Gbps aggregation into 10 Gbps signal). In turn, the ODU mux/demux with transceiver solution allows for any combination of sub-rate signals to be aggregated onto a composite channel so as long the channel’s bandwidth is not surpassed. Lastly, the configuration featuring a single transponder lies appropriate for the cases where the client signal’s rate is a match to the transmission line rate.

**Opaque:** Each network node is equipped with a standalone OTN switch connected to the WDM network via line cards and WDM mux/demux devices. Only sub-wavelength switching is allowed. The WDM network’s solemn purpose is to provide for point to point connections among OTN nodes. Optical channels can only span a single fiber line and the number of virtual hops a connection must endure from source to destination is lower bounder by the physical hop count of the shortest path between such endpoints.

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**IV. ILP Formulations**

The general statement to the traffic grooming problem in cost minimization challenges can be described as follows: given a graph $G(V, E)$ where $V$ corresponds to the network nodes and $E$ to the fiber links connecting them, a set of traffic matrixes $T^u$, each corresponding to the demand in terms of ODU signals of the same rate $u \in U$, a set of available line rates $r \in R$, and the associated costs of the line cards transmitting/receiving on those rates, a virtual topology and the routing of the client signals are to be determined in
achievement of the lowest network expenditures. The problem is constrained by the optical channels’ capacity $C$ that limits the volume of carried connections and by the number of wavelengths $W$ and transceivers $Tr$. OTN switches at all nodes concede for low speed streams to be processed in the electric domain at intermediate nodes and in turn, ROADMs work on the optical layer to allow for optical bypassing of wavelength channels. On the assumption that traffic demand is symmetric the sub-rate signals are routed over bidirectional virtual paths.

Link path models were featured to tackle the cost minimization problem concerning unidirectional line cards and symmetrical traffic requests. A k-shortest path algorithm is used to calculate the routing paths for lightpaths between any two nodes with traffic requests. Mixed line rate formulations for translucent networks are provided and the necessary adaptations to include opaque and transparent configurations are stated.

A. Problem formulation for translucent networks featuring bidirectional line cards

Given the assumption of the symmetry of the traffic matrices, it is only needed to account for the routing of client signals in a single direction. The attained results can then be mirrored to the opposite direction. For every lightpath established to carry traffic in the direct direction, another one is implicitly accounted for to support the routing of the client signals in the reverse direction. As so, two line cards are required to be deployed for every lightpath provided by the solution, one at each end node with both their incoming and outgoing ports occupied.

The notation used, assumptions made and formulation to the cost minimization problem concerning unidirectional cards is as follows:

Notation:

- $A$ stands for the set of network arcs. Each network arc $a \in A$ is an unidirectional representation of a physical connection among two nodes $(s(a), d(a))$ such that there is at least one fiber link among those nodes. A given arc is characterized by $l_a$, the number of optical fibers uniting $s(a)$ and $d(a)$. Given that fibers are deployed in pairs, if we consider arc $a$ from $s(a)$ to $d(a)$ and arc $a'$ such that $s(a') = d(a)$ and $d(a') = s(a)$, then $l_a = l_{a'}$;

- $i$ and $j$ denote the origin and destination of an optical channel, respectively. A given lightpath may traverse one or multiple network arcs;

- $s$ and $d$ stand for the origin and destination, respectively, of an end-to-end traffic request. The end-to-end traffic can be carried over one or more optical channels.

Assumptions:

- The network is displayed in an irregular mesh configuration;

- The transceivers in the network are tunable to any wavelength in the fiber;

- No wavelength converters are available;

- Fiber physical impairments are despised, no constraints placed on the extent of a lightpath and no considerations made regarding the need for amplifiers;

- Each node has unlimited grooming capability, none added or incoming slow speed streams blocked;

- The only factors weighing in on the network’s cost are the line cards. It is assumed that these are the costlier components and as so, the contribution of all other network resources is despised;

- Line cards are bidirectional and transmit and receive signals of the same rate

- Traffic demand is bidirectional;

- Client connections are routed over bidirectional virtual paths. As a consequence, bidirectional lightpaths are deployed carrying traffic between the same end-points in different directions.

Inputs:

- $W$: Number of wavelengths available per fiber link;

- $R$: Set of available line rates. For every lightpath established, a value $r \in R$ is to be assigned. When considering single-line rate networks, it must be assured that $R = \{r_0\}, |R| = 1$, all optical channels deployed with an associate rate $r_0$. In the scope of the current work, 40 and/or 100 Gbps are the considered available line rates;

- $Cr_R$: Variable that stands for the cost of consuming a line card to transmit or receive a signal of rate $r \in R$. Costs are normalized to the cost of the line card corresponding to the lowest line-rate in the network, only the ratios accounted for. $Cr_r = \frac{\text{cost}_{\text{min}}(r, dR)}{\text{cost}_r}$;

- $U$: Set of considered ODU signals’ rates $U$. Each client signal is mapped onto the payload of the low order ODU whose rate is a match to its own (1.25 Gbps → ODU – 0, 2.5 Gbps → ODU – 1, ...);

- $T^U$: Traffic matrices set $T^U$ corresponding to the ODU connection requests. $s, d \in V$, $u \in U$, $t^u_{sd}$ denotes the number of ODU requests of rate $u$ to establish among source-destination pair $(s, d)$. The notation is as follows: every individual connection is referred to as a traffic demand and a group of traffic demands of the same rate between the same end-points is conceived as a traffic request;

- $P_{ij}$: Set of possible paths between node $i$ and node $j$. These paths are calculated in advance in accordance to the k-shortest path algorithm showcased in Appendix B. $P_{ij} = \{P_{ij,0}, \ldots, P_{ij,m}\}, m \leq k$;

- $P_{ij}^A$: Set of possible paths between node $i$ and node $j$ that traverse arc $A$.

Variables:

- $L_{ij}^r$: Number of optical channels of rate $r \in R$ between $i$
and $j$. $L_{ij}^j \in N_0$;

$P_{ij}^{pw}$ Number of lightpaths between $i$ and $j$ routed on path $p_{ij}$ over wavelength $w$. $P_{ij}^{pw} \in N_0$.

Number of ODU signals of rate $u \in U$ between $G_{ij,sd}$ node pair $(s,d)$ routed on lightpaths with endpoints $(i,j)$. $G_{ij,sd}^u \in N_0$.

**Formulation:**

**Objective Function:**

$$\min \sum_{v} \sum_{r} L_{ij}^r \cdot Cr_r + 2 \quad (1)$$

**Constraints:**

$$\sum_{p_{ij} \in p_{ij}} \sum_{w \in W} P_{ij}^{pw} = \sum_{r \in R} L_{ij}^r \quad \forall i,j \in V \quad (2)$$

$$\sum_{v} \sum_{r} L_{ij}^r \leq L_s \quad \forall a, a' \in A \quad w \in W \quad (3)$$

$$\sum_{v} \sum_{r} L_{ij}^r \cdot u^m_{x,s,d} = 0 \quad \forall s, d \in V, d > s; \quad u \in U \quad (4)$$

$$\sum_{v} \sum_{r} L_{ij}^r \cdot u^m_{x,s,d} = 0 \quad \forall s, d \in V, d > s; \quad u \in U \quad (5)$$

$$\sum_{v} \sum_{r} L_{ij}^r \cdot u^m_{x,s,d} = 0 \quad \forall s, d \in V, d > s; \quad u \in U \quad (6)$$

$$\sum_{v} \sum_{r} L_{ij}^r \cdot u^m_{x,s,d} = 0 \quad \forall k \in V, k \neq s, d; \quad d > s; \quad u \in U \quad (7)$$

$$\sum_{v} \sum_{r} L_{ij}^r \cdot u^m_{x,s,d} \cdot u^m_{y,s,d} \leq \sum_{r \in R} L_{ij}^r \cdot r \quad \forall i,j \in V \quad (8)$$

The objective function (1) regards the minimization of the total cost of deploying line cards. The factor of 2 in the objective function is associated with the fact that only the lightpaths carrying connections in the direct direction are considered. As so, a line card is accounted on the source and on the destination of the optical channel. The imposition that another optical channel with matching end nodes must be established to carry traffic in the reverse direction assures that both the incoming and outgoing port are made use of for every card deployed. (2) and (3) concern the physical routing of the lightpaths assuring that for each established optical channel, the same wavelength channel is reserved in all spanned links. Also, (3) assures the wavelength clash constraint by establishing that a wavelength can be assigned to at most one lightpath per fiber link. On the matters of the RWA process, it must be assured that for every link crossed by an established lightpath, the link in the opposite direction with matching end-nodes has the assigned wavelength channel reserved for the reverse lightpath. For such purpose, a new variable was introduced, $a'$ to represent for the opposite link for every link $a$ taken in consideration ($s(a) = d(a')$). Equations (4) to (8) regard the virtual routing of each individual traffic flow, ensuring the assignment of client signals onto a set of one or more lightpaths. Only the direct connections are considered that is, the ones originated at a node with a lower index on the graph than the destination node. Inequation (9) guarantees that connections are assigned to lightpaths as the offered bandwidth is not exceeded.

**V. HEURISTIC**

To tame the NP-complete property of the ILP GRWA formulations, a heuristic approach was developed targeting application to networks of greater reaches to which the mathematical programming approach is often times impracticable. The designed algorithm makes use of the graph model presented in [4] to provide an initial input to be manipulated in achievement of lower costs. Given a set of traffic matrixes, the graph methodology is put to use to satisfy the client demands in their entirety. As a result, a virtual topology and each established lightpath’s routing and wavelength assignment is attained as is the virtual routing of each individual traffic flow over such topology. Using the obtained configuration as a starting point, the purpose of the algorithm is to re-route traffic, rearranging the assignment of connections onto optical channels to eliminate the need for some of the lightpaths in the initial set-up. A lightpath is selected in turn and considered for elimination by exploring alternative virtual routing options to the connections it carries. If a portion or all of its traffic is averted, it may be possible to replace the associate line cards for others of lower cost (replacing a 100 Gbps lightpath with a 40 Gbps one) or to completely discharge the card. Among each node pair connected by means of one or more optical channels, one and only one lightpath is selected and subjected to this process. If the configuration attained after considering all the candidate lightpaths for elimination is of lower cost than before the rearrangement performed, the process is repeated. Otherwise, the algorithm terminates.

**A. Deconstructing the Graph Model inputs**

A set of initial inputs to the cost minimization algorithm is attained by running the graph model in every possible combination of Traffic Selection Schemes and Grooming Policies. For each solution attained, the final graph state representing the lightpaths established, their physical routing, wavelength assignment and demands carried is kept. The obtained set contains the objects to be manipulated in achievement of minimum expenditure. The input variables given by the graph solution to the cost minimization method are:

$L_{ij}$: Set of lightpaths established between $i$ and $j$.

$P_{ij} = \{P_{ij,0}, \ldots, P_{ij,|P_{ij}|-1}\}$. Every lightpath is characterized by its rate $R_{P_{ijk}}$ and by the total volume of demands it carries $d_{w_{ijk}}$.

$W_{ij}$: Set of wavelengths assigned to lightpaths between $i$ and $j$. $W_{ij} = \{w_{ij,0}, \ldots, w_{ij,|W_{ij}|-1}\}$.

$P_{ij}$: Set of physical routes used by lightpaths established.
between $i$ and $j$. $P_{ij} = \{P_{ij,0}, \ldots, P_{ij,y_{ij}}\}$;

$Z_{ij,sd,u}$: Set of demands carried in lightpaths between $i$ and $j$; $z_{ij,sd,u}$ represents the number of demands of rate $u$ between $s$ and $d$;

$A_{ij}$: Total amount of traffic carried in lightpaths between $i$ and $j$: $A_{ij} = \sum_{e \in E} \sum_{d \in \mathcal{D}} \sum_{u \in \mathcal{U}} z_{ij,sd,u}$ normalized to the number of 1.25 Gbps time-slots.

Additionally, the cost minimization algorithm also makes use of the additional following variables:

$Lrem$: List of lightpaths from which traffic is to be averted onto other lightpaths. The lightpaths featured in this list are potential candidates to be fully relieved from traffic and eliminated;

$T_{i}^{out}$: Total amount of traffic carried in lightpaths in list $Lrem$ with node $i$ as their source measured in ODU-0 time slots;

$T_{i}^{in}$: Total amount of traffic carried in lightpaths in list $Lrem$ with node $i$ as their destination measured in ODU-0 time slots;

$C_{i}^{out}$: Spare capacity of the lightpaths in list $Lrem$ with node $i$ as their source measured in ODU-0 time slots;

$C_{i}^{in}$: Spare capacity of the lightpaths in list $Lrem$ with node $i$ as their destination measured in ODU-0 time slots;

$VP_{sd,u}$: Set of virtual paths that allow to carry at least one demand of rate $u$ between $s$ and $d$, $P_{sd,u} = \{P_{sd,u0}, \ldots, P_{sd,uP_{sd,u}}\}$. Every path $P_{sd,u,k}$ is comprised of a set of one or more lightpaths creating a route from $s$ and $d$. The hop count of the virtual path $H(VP_{sd,u,k})$ is given by the number of lightpaths spanned minus one. The capacity of the virtual path $C(VP_{sd,u,k})$ is given by the spare capacity of the most occupied lightpath traversed;

$C_k$: Cost attained running iteration $k$.

One solution is chosen at a time and the correspondent virtual topology deconstructed in such a way that for every node pair with established lightpaths, the lightpaths are rearranged to attain the configuration with the least cost. Post to that, one of the lightpaths in the rearranged configuration is chosen as a potential candidate for elimination from the virtual topology. To determine such configuration as well as the selected lightpath, the following steps must be performed for every pair $(i,j), i, j \in N$:

- **Step 1:** Consider:
  
  $x_{ij}$: Number of 100 Gbps lightpaths between $i$ and $j$;
  $y_{ij}$: Number of 40 Gbps Lightpaths between $i$ and $j$.

  Determine the least costly configuration such that:
  
  $x \cdot T_{S100} + y \cdot T_{S40} \geq A_{ij}$

  $x, y \text{ minimize } (x \cdot C_{r_{100}} + y \cdot C_{r_{40}})$

- **Step 2:** If $(x + y > |P_{ij}|)$, $x + y - |P_{ij}|$ lightpaths must be established. If the spare unassigned wavelength channels in the network’s fiber links allow it to, establish the required lightpaths. Otherwise, maintain the configuration reflected in the final graph state and update the values of $x_{ij}$ and $y_{ij}$.

- **Step 3:** Update $Lp_{ij}$ such that
  
  $Lp_{ij} = \{Lp_{ij,0}, \ldots, Lp_{ij,x+y-1}\}$

- **Step 4:** Given that all optical channels are filled to the most of their capacity but potentially one, assign traffic to the channels seeking that the one with spare capacity, if any, is one from the set of lightpaths with highest rates;

  Insert the lightpath with spare capacity if there is one or one of the lightpaths of highest rate otherwise into list $Lrem$.

**B. Lightpath Selection**

To select the order in which the lightpaths in list $Lrem$ are attended, a weight is assigned to each according to a given Lightpath Selection Scheme. The list is sorted so that optical channels with the lowest associated weight are prioritized over the ones with highest weights. The set of Lightpath Selection Schemes and the formulas to calculate the related weights are as described below:

- **Least Traffic**:
  
  $w_{Lp_{ij,k}} = d_{Lp_{ij,k}}, i \in N, j \in N, k = |Lp_{ij}| - 1$  \hspace{1cm} (10)

- **Node utilization**:
  
  $w_{Lp_{ij,k}} = \frac{T_{i}^{out}}{C_{i}} \cdot 0.5 + \frac{T_{j}^{in}}{C_{j}} \cdot 0.5, i \in N, j \in N, k = |Lp_{ij}| - 1$  \hspace{1cm} (11)

- **Lightpath utilization**:
  
  $w_{Lp_{ij,k}} = \frac{d_{Lp_{ij,k}}}{C_{i}} \cdot 0.5 + \frac{d_{Lp_{ij,k}}}{C_{j}} \cdot 0.5, i \in N, j \in N, k = |Lp_{ij}| - 1$  \hspace{1cm} (12)

**C. Virtual Path Selection Schemes**

Whenever the algorithm tries to eliminate the need for a given lightpath by averting all of its traffic to other already deployed lightpaths, the selection of the virtual routing must be performed for each of the demands carried. The alternative virtual paths must comprise a new set of optical channels that connect the end-points of the demands, averting the lightpath candidate for elimination. Whenever a set of possible virtual routes is available, an order must be imposed to select which one is selected first. Three lines of options were made available:

- **Least Capacity**: The path chosen is the one with the least spare capacity corresponding to the lightpath spanned with highest occupation;

- **Highest Capacity**: The opposed to the scheme above, this approach settles for prioritizing the virtual routes with the most spare capacity;

- **Least Number of Hops**: The selected path is the one from the set that spans the least number of lightpaths.
D. Algorithm Description:
The steps to the algorithm are as follows:

Step 1: Select the first graph model attained solution corresponding to a (Traffic Selection Scheme, Grooming Policy) pair;
Step 2: Select the first Lightpath Selection Scheme;
Step 3: Select the first Virtual Path Selection Scheme;
Step 4: Select the first Virtual Path Selection Scheme;
Step 5: Determine the initial cost \( C_0 \) of deploying the defined virtual topology;
Step 6: For every node pair with connecting optical channels, insert the lightpath with spare capacity if there is one, or one of the established lightpaths of higher rate otherwise, in list \( Lrem \);
Step 7: Sort list \( Lrem \) according to the defined Lightpath Selection Scheme;
Step 8: Select the first lightpath \( Lp_0 \) from list \( Lrem \) and try to deviate as many carried connections as possible to other lightpaths with spare capacity;
Step 9: Update \( A_s(Lp_0)d(Lp_0) \) to reflect an eventual decrease in occupation;
Step 10: If any number of connections were re-routed and removed from \( Lp_0 \), recalculate the least costly lightpath configuration among node-pair \((s(Lp_0), d(Lp_0))\). If the attained configuration is advantageous in regards to cost to the current one, update to such. If the number of lightpaths diminishes, free up the no longer used wavelength resources. Recalculate \( T_{out_{(Lp_0)}}, T_{in_{(Lp_0)}}, C_{out_{(Lp_0)}}, C_{in_{(Lp_0)}} \);
Step 11: Remove the first lightpath from the list. If \( Lrem \) is empty, continue. Otherwise return to step 8;
Step 12: Calculate the cost \( C_{iter} \) of maintaining the current virtual topology. If \( C_{iter} < C_{iter-1} \), return to step 6. Otherwise, continue;
Step 13: Save the final cost in set \( C_{sol} \);
Step 14: Select the next Virtual Path Selection Scheme. If all have been iterated, continue. Otherwise, move to step 4;
Step 15: Select the next Lightpath Selection Scheme. If all have been iterated, continue. Otherwise, return to step 3;
Step 16: Select the next solution from set of graph model attained virtual topologies. If all solutions have been attended, continue. On the contrary, return to step 2;
Step 17: Select the minimum value in set \( C_{sol} \) as the final and most satisfying solution.

VI. RESULTS

A. Ilp Formulations

The current section comprises the results attained for a number of simulations applying the cost minimization Ilp formulation to a seven nodes test network with 10 bidirectional links. The network’s physical topology is displayed in Figure 4. The opaque, translucent and transparent network configuration schemes were put to comparison and conclusions drawn. Regarding translucent scenarios, simulations were conducted assuming the availability of 40 Gbps and/or 100 Gbps lightpaths in single and mixed line rate conditions. A range of cost ratios \{1.5, 2, 2.5\} was considered.

The intent was to access how the relations between the line cards’ costs could impact the obtained costs. Data-rates for the traffic requests were assumed to fit in a set of 1.25, 2 and 10 Gbps. The variation of the cost with the total traffic volume TTV measured in Gbps is presented.

![Figure 4 –Seven nodes test network physical topology](image)

![Figure 5 - Network cost comparison for a set of cost ratios between single and mixed rate networks in translucent scenarios](image)

![Figure 6 - Network cost comparison between opaque, transparent and translucent networks in mixed rate scenarios](image)
attained. On the opposite side, the opaque approach’s obligation that all lightpaths can only span a single fiber link resulted in the highest costs from among all possible configurations for all cost ratios.

B. Heuristic and Ilp Comparison

In order to compare on the performance of the heuristic developed, test nodes with seven and eight nodes were subjected to simulations. Under the same assumptions and conditions as the ones stated above, Ilp and heuristic solutions were attained applying the models presented above to the same scenarios. The focus was laid upon the quality of the solutions attained in comparison to the mathematical model. Only the gaps of the algorithm to the Ilp solutions are showcased.

The results for the seven nodes examined before are as follows:

The presented figures suggest a compelling performance of the heuristic methodology by always providing results within a ten percent window to those of the mathematical programming approach, both for single or mixed line rate scenarios and for the opaque network configuration as well. The computational times observed are only a small portion of the ones required for the mathematical approach as is desired in a heuristic methodology.

VII. APPLYING THE HEURISTIC TO REAL LIFE NETWORKS OF LARGER DIMENSIONS

The NP-complete trait that characterizes Ilp solutions settles as a limitation to the mathematical models, their space of feasibility contracting as the problem’s dimensions expand. As a consequence, their application is only fitting for networks of small dimensions. In order to have results applied to a real life network, the cost minimization heuristic was used. As was the case when performing Ilp simulations, mixed and single line rate scenarios are encompassed as are translucent, transparent and opaque configurations. The results for the cost minimization problem applying the developed algorithm to the Arpanet Network as presented below:
VIII. CONCLUSIONS

The current work presented Ilp methodologies and heuristic approaches to the cost minimization problem. The methodology followed was that of employing traffic grooming techniques to minimize the equipment costs. Expenditures were traced back solely to optical line cards that featured transponders and OTN multiplexers/demultiplexers. Opaque, transparent and translucent models were considered. Mixed and line rate network scenarios also featured in the scope of the work. Results applying the Ilp models showcased a superior performance of translucent, mixed line rate networks against all other network schemes, the coexistence of optical channels of distinct rates in the same fiber alongside the functionality to perform lambda and sub lambda switching providing the most advantages. A heuristic approach was also presented and the results attained for single and mixed rate networks proved to be satisfying when in comparison with the ones obtained by application of Ilp model.

IX. REFERENCES