Multi-layer Traffic Grooming in networks with an IP/MPLS Layer on top of a meshed Optical Layer

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***Abstract*— Traffic grooming in networks employing WDM is gaining attention due to the difference between the bandwidth requirements of the traffic demands coming from the client layer and the capacity of a wavelength in an Optical Transport Network (OTN). In this paper an algorithm for efficient traffic grooming in a multi-layer IP/MPLS-over-meshed OTN scenario is presented. It allows designing the IP/MPLS logical topology best suited to deal with the offered traffic pattern, taking into account the unidirectional and maybe asymmetric character of IP traffic. This multi-layer traffic grooming algorithm is based on the idea of charging the IP/MPLS layer for the capacity it consumes in the optical layer. In order to assess its performance, a comparison with other grooming approaches is made. The results show that our method allows for serious savings in the overall network design cost. It also allows for a gradual capacity installation in the network, thus spreading the installation cost.**

I. Introduction

The introduction of Wavelength Division Multiplexing (WDM) in the optical transport networks has opened a tremendous amount of bandwidth. Line-systems that can transport up to 160 wavelength channels on a single fiber have been presented. Each such a single wavelength channel can have a bit rate of 2.5 or 10 Gbps and research on 40 Gbps channels and up is ongoing.

For the moment, WDM is only deployed in static point-to-point connections. This means that the processing of the traffic takes place at the higher layer(s). In the foreseeable future the envisaged transport network scenario will be IP/MPLS-directly-over-Optical. This means that the traffic processing would thus be conducted in the Internet Protocol (IP) layer with MultiProtocol Label Switching (MPLS) capabilities. The IP/MPLS router technology has indeed been evolving quite a lot in recent years. But nevertheless, the electronic routers have not been able to keep up with the evolution of achievable bit rates in the optical layer. The IP/MPLS routers will thus become the new bottleneck in the transport network now the bandwidth bottleneck in the links has been solved.

With the introduction of Optical Cross-connects (OXCs) it becomes possible to establish a lightpath from origin to destination, thus keeping the traffic in the optical domain. But, as stated above, the wavelength channels making up such a lightpath have a high available bandwidth (10 Gbps, likely to increase to 40 Gbps). There is a quite high difference between the bandwidth requirement of a single client traffic demand (typically in the range of 155 Mbps to 622 Mbps [1]) and the capacity of a wavelength. Precisely this vast difference in the granularity of the bandwidth requirements of the client layer versus the bandwidth offered by the network necessitates the efficient sharing of the capacity of a wavelength by multiple users. In order for the optical transport layer to be cost-efficient, the wavelengths should be properly filled.

This is where traffic grooming (sometimes called optimized consolidation) comes into the picture. Traffic grooming tries to achieve a compromise between the efficient use of the node equipment in the IP/MPLS layer and the transmission equipment in the optical layer of the network. This is schematically explained in Figure 1. In (a), more wavelengths than necessary are used in the Optical Transport Network (OTN) layer. These wavelengths will also have a quite low filling. (b), on the other hand, lies an unnecessary high burden on the IP/MPLS layer node equipment, as in every network node the traffic is passed to the IP/MPLS layer, processed in the IP/MPLS router and, if it is not terminated in that IP/MPLS router, passed back to the optical layer. In (c) the right trade-off between wavelength channel usage in the optical layer and IP/MPLS node usage is achieved.

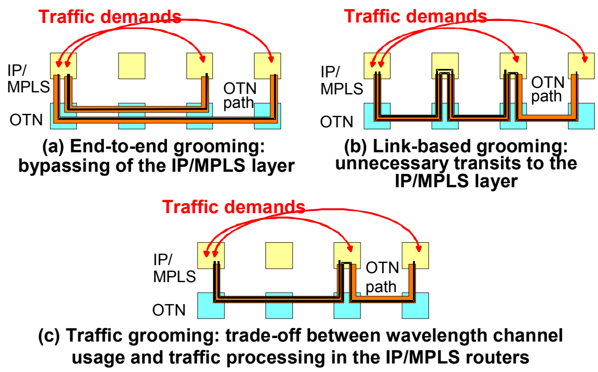

Figure 1. The principle of traffic grooming.

The goal of an efficient grooming algorithm is thus to minimize the overall network cost and at the same time use the resources in the network as efficiently as possible. However, grooming is more than the routing and grouping or bundling of the IP/MPLS traffic streams in the higher order wavelength channels. Grooming also includes the topological design of the networks themselves [2]. This means that an appropriate grooming algorithm can design the logical topology of the

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IP/MPLS layer, and use a candidate physical topology in the most advantageous way.

In literature, the topic of traffic grooming has already been studied, but most of the work concentrated on ring-based networks (e.g. [3-6]). Reference [7] gives an excellent overview of the work done on grooming in (mostly ring-based) WDM networks. Research on traffic grooming in meshed optical networks has however only been conducted to some extent (e.g. [8-9]), but much work remains to be done. In most cases, only the equipment cost of a single layer of the multi-layer network gets optimized, or both layers are optimized independently, without any information being fed back from one layer to another. Furthermore, most work has been focussed on the traffic grooming of SONET/SDH demands in the wavelength channels of the optical network. Input to the grooming algorithm are the bidirectional traffic demands expressed in number of STM-Xs (X is e.g. 1, 4, 16) that have to be groomed into lightpaths.

Our work takes into account that voice traffic is no longer the dominant traffic type, but has been overtaken by data traffic, which is unidirectional. The client layer is thus an IP network with MPLS functionality and the traffic that is offered to this IP/MPLS client network can be unidirectional. Even more, the algorithm is able to handle an asymmetric traffic demand, which is quite plausible as several applications transported over IP (with HTTP-based traffic as the much quoted example) send more traffic in one direction of the connection than in the other [10]. The optical network layer is assumed to have a meshed topology. The algorithm that is discussed in this paper is a two-layer traffic grooming algorithm, with a feedback mechanisms to ensure an optimal overall network cost. An IP/MPLS logical topology is designed in which the traffic demand is groomed, and the IP/MPLS layer capacity demand gets assigned wavelengths in the optical network, in a cost-minimizing way.

The structure of this paper is as follows. In Section II, the problem is formulated. Section III explains the methodology used to tackle the multi-layer traffic grooming problem in an IP/MPLS-over-Optical transport network. In Section IV, some other approaches are explained. Section V introduces and discusses a case study. Section VI formulates the conclusions.

II. PROBLEM FORMULATION

The problem we want to solve can be formulated as follows:

Given:

- an existing physical topology consisting of a number of nodes where IP/MPLS routers and OXCs are installed, and a number of bidirectional links (fibers) interconnecting these nodes (this will be called the candidate physical topology in the remainder of the paper), and
- a traffic matrix which serves as input to the IP/MPLS layer (this traffic matrix can contain unidirectional and even asymmetric traffic).

Find:

- the logical IP/MPLS topology,
- the routing of the traffic demand on this IP/MPLS logical topology, and
- the routing of the capacity demand from the IP/MPLS layer on the candidate physical topology

that minimizes the overall network cost, while taking into account the traffic demand pattern.

In this paper, the IP/MPLS layer topology is assumed to be unidirectional (both directions of a logical IP link don't necessarily have the same amount of capacity). The optical layer however is bidirectional, or the same amount of capacity is installed on both directions of the optical links.

III. MULTI-LAYER TRAFFIC GROOMING ALGORITHM

The algorithm that was designed to solve this problem is an iterative one, based on the idea of charging the IP/MPLS logical layer for the resources it uses in the optical layer to support the logical IP/MPLS topology [11] (see Figure 2).

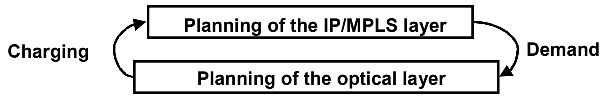

Figure 2. The IP/MPLS layer is charged for the optical resources it uses

This algorithm is based on the one explained in [11]. There are however some important differences. One of them is the fact that the client layer is now assumed to be an IP/MPLS-based network that is unidirectional and is able to accommodate in a very efficient manner the unidirectional and maybe asymmetric IP traffic demand [10]. Also the feedback loop (this will be explained further on) is different. This algorithm consists of several steps:

A. *STEP 1: problem initialization*

Starting from a fully meshed IP/MPLS topology, the traffic demand is routed on the unidirectional logical topology. This results in a traffic demand to the optical layer, which is in this initialization step routed on the candidate physical topology along the least cost path. In this first step the cost of a single wavelength on a link in the optical layer is simply the cost of a fully capacitated line-system divided by the number of wavelengths this line-system can support (e.g., when a line-system of 40 wavelengths has a cost X, each wavelength is assigned a cost equal to X/40). This gives a very first estimation of the capacity needed in the optical layer, but, more important, this allows us to assign a cost to the IP/MPLS links based on the cost for supporting these links in the optical layer.

The method used for deriving this cost and thus the feedback loop in our multi-layer algorithm, is quite straightforward: an IP link gets assigned a cost proportional to the filling of the line-systems along its route in the optical layer. An IP/MPLS link that is for instance routed along 2 consecutive optical links with 40-channel line-systems that are 20% filled, gets assigned a cost of 2*((cost of a line-system)/40)*5. All links in the fully meshed IP/MPLS topology now have a cost assigned to them.

Now the problem has been initialized, we can start tackling the traffic grooming problem.

B. STEP 2: grooming in the IP/MPLS layer

Traffic is groomed on the unidirectional IP/MPLS logical topology using the Forward Synthesis and Design Tightening algorithm. This is a two-stage Minimum Cost Capacity Installation (MCCI) problem [12]. In the Forward Synthesis (FS) stage, the network is dimensioned to carry all the traffic demands. In the second, Design Tightening (DT) stage the results obtained in the first stage are improved by dropping underused facilities and rerouting this part of the traffic. Figure 3 and 4 show the flowcharts of both stages of the algorithm.

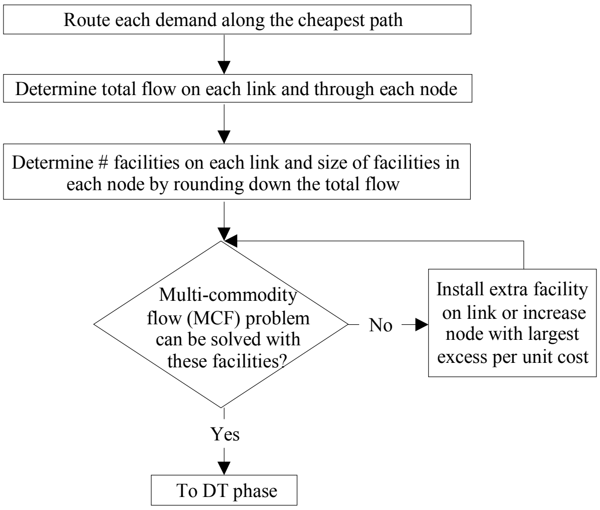

Figure 3. Forward Synthesis stage of the two-stage MCCI algorithm

The MCCI problem determines the (set of) fixed capacity system(s) that needs to be installed on each link and node in the network in order to allow simultaneous routing of all demands and has as objective to minimize the total installation cost of the systems.

At the end of STEP 2, the IP layer topology has been designed taking into account both the traffic demand and an estimation of the cost for supporting the logical topology in the optical layer. This step gives us also the traffic demand for the underlying optical layer.

C. STEP3: grooming in the optical layer

The traffic is now groomed on the bidirectional optical candidate topology, again using the Forward Synthesis and Design Tightening MCCI algorithm. At the end of this step, the optical layer has been dimensioned taking into account both the traffic demand coming from the IP/MPLS layer and the cost of the network design. Not all links of the physical candidate topology are necessarily used. It might be that on some links no line-systems need to be installed.

At this stage of the multi-layer traffic grooming algorithm the total cost of the IP/MPLS and optical layer designs can be calculated.

D. STEP 4: feedback loop

In step 4 information is fed back from the optical layer to the IP/MPLS layer in order to improve the overall network cost and the IP/MPLS logical network topology design. As in the first initialization step, the feedback information is based on a charging system. Again the IP layer is charged for using capacity in the underlying optical layer. Again, an IP link gets assigned a cost proportional to the filling of the line-systems along its route in the optical layer. But instead of changing the cost of the links in the IP layer in this sometimes very drastic way, a Inertia Factor α has been built in. The used Charging Factor (CF) for an IP/MPLS link is now a weighted sum of the previous charging factor and the newly calculated one:

$$CF_{link\ x\text{-}y} = \alpha * \text{previous } CF_{link\ x\text{-}y} + (1-\alpha) * \text{new } CF_{link\ x\text{-}y} \quad (1)$$

The algorithm (denoted as FS+DT↔FS+DT in the remainder of this paper) then iteratively performs steps 2, 3 and 4 until it is stopped at step 3.

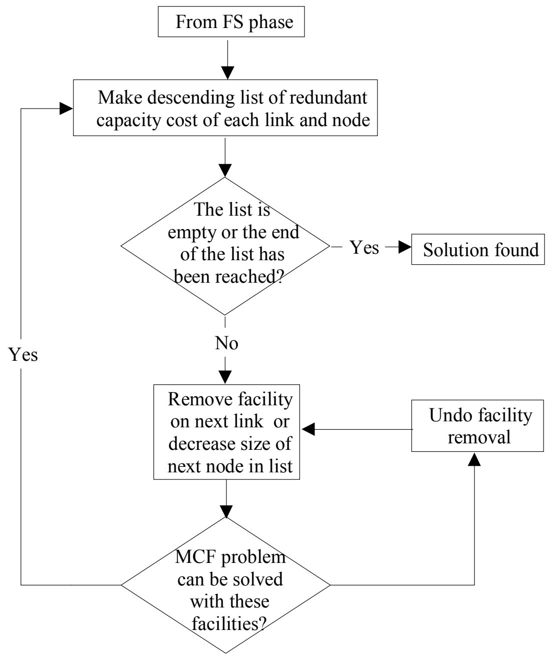

Figure 4. Design Tightening stage of the two-stage MCCI algorithm

The performance of the heuristic has been assessed for several values of the inertia factor α. The best results for the overall network cost were obtained with an inertia factor α of 0.5. When α equals 0, the feedback charging factor is in some instances too extreme. Logical IP links whose corresponding lightpaths were routed along a route that included a (number of) marginally used optical links get assigned a very high cost at the start of step 2, and is thus avoided by the MCCI algorithm in the IP/MPLS layer, even though the use of this expensive IP/MPLS link was justified as it allowed a lower-cost network design. When α reaches a value close to 1, the effect of the charging factor becomes too small in some cases and prohibits meaningful and important changes in the second step (design of the IP/MPLS layer).

IV. OTHER APPROACHES

In order to assess the performance of the above-described multi-layer traffic grooming algorithm with a charging-based feedback loop, we compare it with an approach that is more or less similar to the one suggested in [9] and [7]. In the latter approach, the first step consists of designing the logical IP/MPLS topology with the least possible number of (fixed-capacity) lightpaths. This is equivalent to minimizing the electronic installation cost in the logical IP/MPLS layer as each link represents a lightpath and each lightpath requires the appropriate electronics for terminating and processing the terminated traffic. This is more or less similar to the above-described two-stage FS+DT heuristic. The cost of the IP links is derived from a shortest path routing on the underlying physical topology. Starting from a full mesh IP/MPLS network the FS+DT MCCI algorithm is applied. At the end of this step, the topology of the IP/MPLS layer has been designed. As suggested in [7], in a second step, the IP/MPLS capacity demand is routed on the optical layer network using a simple and straightforward shortest path (SP) (in terms of cost) routing and dimensioning algorithm. At the end of this step, the candidate physical topology has been dimensioned and the total network cost can be calculated. This algorithm is denoted as FS+DT→SP in the remainder of this paper.

Another variant on this latter approach would be to use the FS+DT algorithm to determine the capacity that needs to be installed in the optical network instead of the SP routing. This approach is denoted FS+DT→ FS+DT.

V. Case Study

In this section some results obtained with the three above-described algorithms (FS+DT↔FS+DT, FS+DT→FS+DT, and FS+DT→SP) are discussed. As test network we have chosen an European optical backbone network, based on the ones described in [13] and [14].

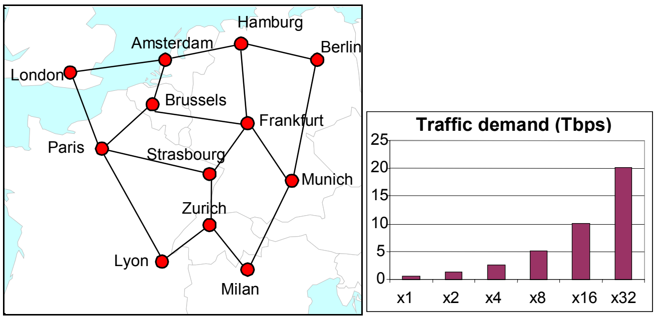

Figure 5. European candidate physical topology and the overall traffic demand offered to this network

The traffic forecast for this network for 2002 and the cost model for the IP/MPLS and optical equipment were also taken from [13] and [14]. The traffic demand of 2002 was then increased (multiplied by a factor of 2, 4, 8, etc.) to see the influence of increasing traffic.

The cost model [15] used in this study takes into account:

- the line cost: cost of the fiber (including the cost for e.g. digging the duct) and the optical amplifiers,
- the WDM line-system cost: cost of the mux/demux, the amplifier and the long-reach transponders,
- the OXC cost: this depends on the size of the OXC needed, and includes the cost of the tributary cards and an estimation of the cost of the management system,
- the IP router cost: this cost also includes the needed router line cards.

This cost model is very important, as in a traffic grooming algorithm, much of the outcome depends of course on the cost ratio between the transport cost in the optical layer and the IP/MPLS router processing cost. We would like to stress that the figures in our cost model are realistic ones, obtained from discussions with European network operators.

A very important result is of course the performance of the three algorithms in terms of cost. Figure 6 illustrates the total installation cost of the IP/MPLS and optical layer obtained with the three algorithms for the traffic of 2002 and several multiplication factors. As can be seen, the proposed FS+DT↔FS+DT algorithm performs the best. Just how much better than the other two is shown in Table I. For a multiplication factor of 1, a cost advantage of 31% is reached compared to FS+DT→SP, but this diminishes gradually to around 8% for a multiplication factor of 32.

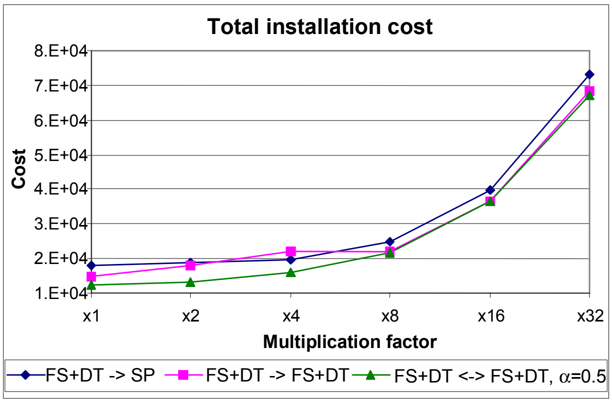

Figure 6. Total network installation cost (IP/MPLS and optical layer) obtained with the three discussed traffic grooming approaches

TABLE I. COST DECREASE OBTAINED WITH FS+DT↔FS+DT COMPARED TO THE OTHER TWO APPROACHES

	Cost decrease between FS+DT→SP and FS+DT↔FS+DT	**Cost decrease between FS+DT→FS+DT and FS+DT↔FS+DT**
x1	31.4%	15.0%
x2	29.4%	26.1%
x4	18.8%	27.6%
x8	13.7%	1.6%
x16	8.2%	0.2%
x32	8.4%	1.7%

From Table I it is clear that a SP routing on the optical layer gives rise to a quite large extra cost. Applying instead the FS+DT algorithm, decreases the cost of the overall network design, but it is obvious that the feedback loop accounts for an additional cost decrease. The amount of this additional cost decrease is significant for a rather low traffic load. For a very high traffic load, the influence diminishes. This cost difference between the three approaches can be explained by a number of things.

Let us first look at the optical layer. Table II quantifies the evolution of the optical layer over time for the three algorithms. With FS+DT↔FS+DT and FS+DT→FS+DT, the capacity demand coming from the IP/MPLS layer is really groomed into the candidate optical links, as opposed to FS+DT→SP. This implies that with FS+DT↔FS+DT and FS+DT→FS+DT not all candidate links are actually used. In fact, in Table II we see that with FS+DT↔FS+DT the number of used optical links increases gradually from 11 for a multiplication factor of 1 and 2, to 17 for a multiplication factor of 32. For each intermittent multiplication factor, capacity (optical line-systems) needs to be installed on some extra links. With FS+DT→SP, all links are employed from the beginning. The filling of the line-systems is thus more efficient with FS+DT↔FS+DT than with FS+DT→SP (Table III). This difference in filling decreases however as traffic increases: the advantage of grooming the lightpaths into the line-systems decreases as the traffic demand reaches the level of the capacity installed in the optical layer. As the cost of the optical equipment is quite high compared to the cost of the IP equipment, the FS+DT↔FS+DT evolves to a solution with quasi minimum number of employed line-systems in the optical network layer, even if this means that more IP links are needed. This explains the difference with FS+DT→FS+DT.

Besides this, also the IP/MPLS logical topology shows a difference (in evolution). With the three algorithms the logical topology evolves to a full mesh (end-to-end grooming), but with FS+DT↔FS+DT and FS+DT→FS+DT this evolution goes slower than with FS+DT→SP. The filling of the IP/MPLS links (see Table III) is however quite high for all cases as the FS+DT algorithm has proofed to be a very efficient one. As said before, because of the dominant cost of the optical layer equipment, the FS+DT↔FS+DT algorithm evolves to a solution with minimum amount of installed optical line-systems, as opposed to FS+DT→FS+DT, but with more IP/MPLS links. As there are less IP/MPLS links in the solution found with FS+DT→FS+DT, and the FS+DT algorithm is very efficient, the filling of the IP/MPLS links is higher for FS+DT→FS+DT than for FS+DT↔FS+DT.

The results also clearly indicate that the feedback loop ensures that the overall network cost evolves to a minimum value. When the initial estimation isn't a good choice, the feedback loop allows reaching a good overall result. Without the feedback loop the result depends completely on the first attempt to minimize the overall network cost. For high traffic loads, the difference between FS+DT→FS+DT and FS+DT→SP is however very small, again because the traffic demand coming from the IP/MPLS layer reaches the level of the capacity installed in the optical layer.

TABLE II. EVOLUTION OF THE IP/MPLS TOPOLOGY DESIGN AND THE USE OF THE CANDIDATE PHYSICAL TOPOLOGY WITH INCREASING TRAFFIC

	# unidir IP/MPLS links			# bidir optical links		
	FS+DT → SP	FS+DT → FS+DT	FS+DT ↔ FS+DT	FS+DT → SP	FS+DT → FS+DT	FS+DT ↔ FS+DT
x1	70	59	65	17	13	11
x2	102	37	75	17	15	11
x4	125	68	106	17	15	13
x8	131	119	123	17	16	16
x16	132	128	130	17	17	17
x32	132	131	132	17	17	17

TABLE III. EVOLUTION OF THE FILLING OF THE IP/MPLS LOGICAL LINKS AND OF THE LINE-SYSTEMS INSTALLED IN THE CANDIDATE OPTICAL TOPOLOGY

	Filling unidir IP/MPLS links			Filling bidir optical line-systems		
	FS+DT → SP	FS+DT → FS+DT	FS+DT ↔ FS+DT	FS+DT → SP	FS+DT → FS+DT	FS+DT ↔ FS+DT
x1	92.7%	98.2%	91.7%	10.8%	35.8%	25.7%
x2	97.1%	99.4%	97.8%	20.4%	70.6%	50.5%
x4	98.8%	99.4%	99.3%	39.8%	64.2%	62.7%
x8	98.9%	98.9%	99.5%	64.1%	85.8%	82.7%
x16	99.9%	99.9%	99.8%	78.8%	89.6%	89.5%
x32	99.9%	99.8%	99.8%	84.9%	93.5%	95.4%

VI. CONCLUSION

In this paper we have described a multi-layer traffic grooming algorithm for an IP/MPLS-over-optical network. Where most of the research on traffic grooming has been focusing on ring networks, in our algorithm we have assumed a meshed optical layer network topology. This is appropriate as in today's backbone networks the transition is being made from networks arranged in rings to general mesh topology networks, due to e.g. the growth of IP data traffic. Our algorithm also has the possibility to take into account the asymmetric nature of the traffic offered to the IP/MPLS layer (mainly due to the IP traffic). The obtained results demonstrate the efficiency of our multi-layer traffic grooming algorithm compared to other approaches. A significant cost reduction was obtained for the overall network cost.

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