Cost minimization on OTN Interfaces: An ILP-based planning model

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***Abstract*—This paper introduces a practical approach to optimize Optical Transport Networks (OTNs) interfaces by the proposal of an Integer Linear Programming (ILP) mathematical model. The presented model focuses on minimizing the number of deployed OTN interfaces, the most costly element in the network, to reduce operational costs while meeting the aggregate traffic requirements. It considers various factors such as the network topology, different classes for the traffic demands, distinct-capacity interfaces and resource constraints. Extensive simulations were conducted and demonstrated the model's ability to find optimal solutions within short computation times, thereby improving resource utilization in the network.**

***Index Terms*—Optical Transport Network (OTN), Integer Linear Programming (ILP), Optimization, OTN Interfaces.**

I. Introduction

In recent years, the world has witnessed a remarkable emergence of revolutionary internet technologies and bandwidth-intensive applications, such as ultra-high-resolution video, virtual reality and 5G mobile network. This surge has triggered an explosive increase in network traffic, especially due to COVID-19 pandemic, which has further intensified society's reliance on digital services [1].

Optical Transport Networks (OTN) have been proposed as a potential and promising technology to support not only 5G [1], but also future-generation networking systems, such as 6G networks, with their increasing performance requirements [2].

Typically relying on an OTN over WDM (Wavelength Division Multiplexing) layered configuration (Fig. 1), wherein the former layer operates at the electric level and the latter layer at the optical level, Optical Transport Networks enables a more efficient utilization of optical layer resources [3].

In order to ensure efficient and cost-effective network operations, the planning of optical networks has emerged as an important research subject. Several techniques have been employed in the literature to tackle different optimization problems in the domain of OTNs. These include Multi-objective Evolutionary Algorithms [3][4], Heuristic Algorithms [5], as well as Integer Linear Programming (ILP) models [6], among others. Nevertheless, it is worth mentioning that in some of these cases the optimal solution is not guaranteed.

This paper presents a novel ILP formulation for interface arrangement in OTN networks. When compared to other solution methods for this problem, ILP ensures globally optimal solutions and efficiently handles multiple aspects of the problem simultaneously, such as demand aggregation, routing and interface placement in complex network structures, including different types of demands, multiple technologies and various constraints. However, it might face challenges with scalability and complexity due to the exponential growth in computation time with network increase. Aditionally, its effectiveness relies on solver quality and real-time adaptability is limited.

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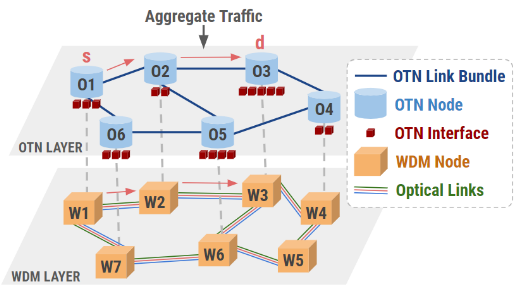

Fig. 1: Example of OTN over WDM layered configuration.

The proposed formulation introduces a comprehensive concept that incorporates the aggregation of multiple service classes onto distinct-capacity interfaces, each associated with specific costs, and representing different transmission rates. To the best of our knowledge, this work is the first to propose such a generalized ILP formulation approach. By utilizing the presented model, the OTN network can be configured in a versatile and adaptable manner, effectively meeting the diverse requirements of various traffic demands.

II. OTN Statement

This paper addresses the problem of planning the OTN network layer over a WDM network. The objective is to efficiently aggregate existing classes of demands on distinct-capacity interfaces, routing them through virtual links and determining the minimal number and strategic placement of required OTN interfaces in order to minimize the capital expenditures (CapEx).

A graphical representation of the multilayer network model considered in this work is presented in Fig. 1. Each node W from the WDM layer may have zero or more OTN nodes O associated with it and each OTN node O can accommodate zero or more interfaces I. In the given example, OTN node $O1$ is associated with optical node $W1$.

The connection possibilities between two OTN nodes are called Link Bundles, which are internally associated to a group of optical fibers from the optical layer. Basically, a Link Bundle addresses whether it is feasible or not to the WDM layer to establish a lightpath for such specific-capacity interface.

Each Link Bundle can accommodate zero or multiple connections between a source-destination pair of interfaces. Since in this work we assume distinct-capacity interfaces, each of such category of interface is associated to a specific Link Bundle topology.

III. ILP FORMULATION

In this section, the proposed ILP formulation and its explanation are presented. The formulation takes into account the existence of different classes of traffic demands, each characterized by its specific required bit rate, with the objective of assigning these demands to OTN interfaces capable of accommodating the corresponding transmission bit rates. Table I summarizes the parameters and variables utilized in our proposed ILP modeling.

Consider a demand k belonging to class b with a requested bit rate of r_b Gbps. This demand can be assigned to an interface with a transmission bit rate of r_c Gbps if and only if $r_c \geq r_b$. Notice that there is a limit on the number of demands of each class that can be assigned to an interface, since assigned demands' aggregated bit-rate cannot overtake the interface capacity.

In order to be able to accommodate all possibilities of traffic aggregation in the available distinct-capacity interfaces, we define in this paper the different forms f how an interface from class c may be filled with demands in $\mathcal{B}$, which is denoted by the vector $\mathcal{I}_f^c$, where position i in $\mathcal{I}_f^c$ refers to the maximum number of allowed i-class demands supported by interface of class c under the form f. Considering a scenario in which the number of classes of demands and the number of classes of interfaces are $|\mathcal{B}| = |\mathcal{C}| = 3$, and the classes' bit rate are $r_1 = 10$ Gbps, $r_2 = 40$ Gbps and $r_3 = 100$ Gbps:

- for 10 Gbps interfaces ($c = 1$), there is a unique feasible form, that is: $\mathcal{I}_1^1 = [1, 0, 0]$, since, in this case, only one demand from class $b = 1$ occupies the entire capacity of the interface;
- for 40 Gbps interfaces ($c = 2$), there are two possibilities, which are: $\mathcal{I}_1^2 = [4, 0, 0]$ and $\mathcal{I}_2^2 = [0, 1, 0]$;
- for 100 Gbps interfaces ($c = 3$), there are four possibilities of configuration: $\mathcal{I}_1^3 = [10, 0, 0]$, $\mathcal{I}_2^3 = [6, 1, 0]$, $\mathcal{I}_3^3 = [2, 2, 0]$ and $\mathcal{I}_4^3 = [0, 0, 1]$.

– Objective Function:

$$\text{Min} \sum_{c=1}^{|\mathcal{C}|} \zeta_c \, I_c \tag{1}$$

– subject to:

$$\Lambda^{s,d,k} = \sum_{b=1}^{|\mathcal{B}|} \gamma_b^{s,d,k} \leq 1 \qquad \forall s, d, k \tag{2}$$

$$\sum_j B_{i,j}^{s,d,k} - \sum_j B_{j,i}^{s,d,k} = \begin{cases} \Lambda^{s,d,k}, & \text{if } i = s; \\ -\Lambda^{s,d,k}, & \text{if } i = d; \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

TABLE I: Inputs and variables used in the mathematical model.

Notation	Description
(Inputs)	
s, d	Source and destination nodes of the traffic demands on virtual topology;
i, j	Originating and terminating nodes of a potential variable-bandwidth lightpath on virtual topology (Link Bundle);
$\mathcal{B}$	Set of classes of demands, where $b = 1 \ldots |\mathcal{B}|$ represents the b-th class of demand and $|\mathcal{B}|$ is the total number of classes of demands;
$\mathcal{C}$	Set of classes of interfaces, where $c = 1 \ldots |\mathcal{C}|$ represents the c-th class of interface and $|\mathcal{C}|$ is the total number of classes of interfaces;
$|\Omega^{s,d}|$	Number of traffic demands between s and d nodes;
$\gamma_b^{s,d,k}$	A binary parameter to indicate whether the k-th demand (where $1 \leq k \leq |\Omega^{s,d}|$) between nodes s and d is a b-class demand ($\gamma_b^{s,d,k} = 1$) or not ($\gamma_b^{s,d,k} = 0$);
$\Lambda^{s,d,k}$	A binary parameter to indicate whether the k-th demand exists ($\Lambda^{s,d,k} = 1$) between the nodes s and d or not ($\Lambda^{s,d,k} = 0$);
$\mathcal{L}_c^{i,j}$	Link Bundle Indicator. $\mathcal{L}_c^{i,j} = 1$ if there is a c-class Link Bundle between nodes i and j, and $\mathcal{L}_c^{i,j} = 0$, otherwise;
$\mathcal{I}_f^c$	A representation for the various forms f that can be assumed by a c-class interface under its traffic limit;
$|\mathcal{I}^c|$	Total number of forms in which a c-class interface can be arranged in its traffic limit;
$\mathcal{I}_{f,b}^c$	Number of b-class traffic demands that can be allocated on a c-class interface, under the form f;
ζ_c	The cost of a c-class interface;
$\mathcal{M}$	A large number.
(Variables)	
$B_{i,j}^{s,d,k}$	Binary variable that indicates whether the k-th traffic demand between nodes s and d is routed ($B_{i,j}^{s,d,k} = 1$) or not ($B_{i,j}^{s,d,k} = 0$) through the virtual link i-j;
$T_b^{i,j}$	Number of demands from class b that pass through the virtual link i-j;
$I_f^{i,j,c}$	Number of interfaces installed on $\mathcal{L}_c^{i,j}$ that are configured in the $\mathcal{I}_f^c$ form;
$I_c^{i,j}$	Number of c-class interfaces that are allocated in $\mathcal{L}^{i,j}$.
I_c	Total number of c-class interfaces allocated in the network.

$$\sum_j B_{i,j}^{s,d,k} \leq 1 \qquad \forall s, d, k, i \tag{4}$$

$$B_{i,j}^{s,d,k} \, \gamma_b^{s,d,k} \prod_{c=1 | r_c \geq r_b}^{|\mathcal{C}|} \left(1 - \mathcal{L}_c^{i,j}\right) = 0 \qquad \forall\, c, s, d, k, i, j. \tag{5}$$

$$T_b^{i,j} = \sum_{s,d,k} B_{i,j}^{s,d,k} \gamma_b^{s,d,k} \qquad \forall\, b, i, j. \tag{6}$$

$$\sum_{c=1}^{|\mathcal{C}|} \sum_{f=1}^{|\mathcal{I}^c|} \mathcal{I}_{f,b}^c \, I_f^{i,j,c} \, \mathcal{L}_c^{i,j} \geq T_b^{i,j}, \qquad \forall i, j, b. \tag{7}$$

$$I_c^{i,j} = \sum_{f=1}^{|\mathcal{I}^c|} I_f^{i,j,c}, \qquad \forall i, j, c. \tag{8}$$

$$I_c^{i,j} \leq \mathcal{M} \, \mathcal{L}_c^{i,j}, \qquad \forall i, j, c. \tag{9}$$

$$I_c = \sum_{i,j} I_c^{i,j}, \qquad \forall c. \tag{10}$$

A. Explanation

Expression (1) is the objective function, which works to minimize the cost in terms of the number of interfaces and their associated individual costs for meeting all demands. Constraint (2) indicates that a demand k between nodes s and d can only belong to a single class b. The conservation of traffic flow at the nodes of a virtual link for each demand is expressed by (3). Constraint (4) indicates that each individual traffic can only be forwarded to a single output lightpath, that is, it cannot be divided across multiple lightpaths. Constraint (5) indicates that traffic from class b can only be forwarded along a lightpath between nodes i-j if there is for these nodes at least one available

Link Bundle that can admit b-class demands. And constraint (6) represents the total amount of b-class demands assigned to lightpaths between nodes i and j. Constraints (7) and (8) work with the interface forms, and (9) and (10) calculate the total number of required distinct-category interfaces.

IV. Simulations

This section discusses the strategy used to build the framework for the discussed optimization ILP problem and presents some results and discussions of two analyzed scenarios.

Case I

s \ d	1	2	3	4	5	6
1	-	1	1	1	1	1
2	1	-	1	1	1	1
3	1	1	-	1	1	1
4	1	1	1	-	1	1
5	1	1	1	1	-	1
6	1	1	1	1	1	-

Case II

s \ d	1	2	3	4	5	6
1	-	1	2	1	1	3
2	2	-	3	2	3	1
3	1	3	-	3	2	1
4	1	1	3	-	3	1
5	1	3	1	3	-	2
6	3	1	1	1	2	-

Fig. 2: Demand classes b for each source-destination (s-d) pair on 6-node network used in simulations. Values 1, 2 and 3 represent classes $b = 1$, $b = 2$ and $b = 3$, respectively.

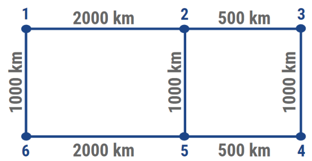

Fig. 3: Small network, with six nodes, used for simulations.

A. Optimization Strategy

In this subsection, we present some analysis of our proposed approach for the solution of the OTN planning problem. The strategy is represented by the following 2 steps:

1 **Initial Link Bundle Settings:** At this stage, Link Bundles for every classes are assigned to the input parameters in ILP. Each class has a specific physical distance limit. Therefore, the Link Bundles will be defined by their corresponding maximum reach.

2 **ILP:** Receives the Link Bundle topology and defines the number of interfaces for each Link Bundle, considering the cost assignment for them.

B. Results and Evaluation

For evaluating the effectiveness of the proposed optimization strategy, the topology shown in Fig. 3 was considered. The parameters were chosen as follows: $|\mathcal{B}| = |\mathcal{C}| = 3$, with transmission bit rates of $r_1 = 10$ Gbps, $r_2 = 40$ Gbps and $r_3 = 100$ Gbps, and their corresponding interface costs defined as $\zeta_1 = 2$, $\zeta_2 = 4$ and $\zeta_3 = 8$. Additionally, the maximum reach for the definition of each Link Bundle in step 1 was set to 4000 km, 2000 km and 1000 km for Link Bundles belonging to classes 1, 2, and 3, respectively.

The IBM ILOG CPLEX v.11.0 was used on an Intel i7 3.6 GHz 32 GB machine to solve the strategy in 6-node network with the classes for each source-destination pair demand defined by the cases I and II in Fig. 2. The performance of the ILP optimization was compared between the different cases.

Tables II and III present the results of minimizing the total cost for different traffic demand scenarios. As expected, the cost escalates proportionally to the number of demands ($|\Omega^{s,d}|$) per source-destination pair. In Case I, in which all demands belong to the same class, the cost rises from 52 to 580 as the number of demands grows from 1 to 15 (an increase of approximately 11.2 times) indicating potential cost savings and improved resource utilization with increasing demand.

Furthermore, the proposed model consistently achieves simulation times below 0.8 seconds for all cases in the 6-node network. This demonstrates the model's efficiency in terms of execution time, enabling quick and effective network planning solutions for real-world applications.

TABLE II: **Case I**. Simulation results for several OTN planning request cases from Fig.2, for any $k \leq |\Omega^{s,d}|$.

$\lvert\Omega^{s,d}\rvert$	(I_1, I_2, I_3)	Obj function (cost)	Simulation time
1	(2, 12, 0)	52	0.14s
5	(10, 28, 8)	196	0.56s
10	(32, 44, 18)	384	0.8s
15	(58, 64, 26)	580	0.8s

TABLE III: **Case II**. Simulation results for several OTN planning request cases from Fig.2, for any $k \leq |\Omega^{s,d}|$.

$\lvert\Omega^{s,d}\rvert$	(I_1, I_2, I_3)	Obj function (cost)	Simulation time
1	(7, 8, 10)	126	0.60s
5	(7, 43, 52)	602	0.20s
10	(0, 91, 105)	1204	0.30s
15	(0, 134, 157)	1792	0.31s

V. Conclusion

This work has proposed an ILP formulation for designing networks with OTN nodes. The presented approach has demonstrated its effectiveness in minimizing the network cost and achieving optimal resource allocation while satisfying demands from different classes. Simulations conducted on a 6-node network have shown that the proposed model is capable of achieving these objectives within short computation times. Additionally, the model's adaptability has been demonstrated through its application to multiple demand classes onto distinct-capacity interfaces. Future work could assess the proposed methodology in larger and more complex topologies, resembling real scenarios. Furthermore, we could explore additional optimization objectives, such as wavelength assignment and fault tolerance.

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