2022 International Conference on Optical Network Design and Modelling (ONDM)

Resources Optimization for a Resilient Time-Shared Optical Network

K. D. R. Assis, R. D. Oliveira, E. Arabul, R. Wang, R.C. Almeida Jr, R. Nejabati, D. Simeonidou

***Abstract*—-Current fronthaul and backhaul networks require innovative technologies to support the key 5G performance indicators such as high bandwidth and sub-millisecond latency. In order to find optimal paths in a multitenant network architecture, we have proposed and applied a mixed linear programming formulation (MILP) to a resilient time-shared optical network (TSON) with multi-level programmability. The goal is to provide an analytical formulation which considers two different objective functions over a physical network substrate taking into account multi-fiber routing and cost constraints. We have run the model for an operational TSON node in a simulated metro-network with six nodes, cross-conectors and different physical capabilities between them. The correlation between minimizing the maximum number of ports/fibers used for node and the total number of fibers for the bundles was tested and the strategy can optimize the network design according to the designer's resource availability or network requirements.**

***Index Terms*—Time-Shared Optical Networks (TSON), Optimization, Resilient Network.**

I. Introduction

In recent years, Optical Transport Networks (OTNs) have become a rapidly thriving area of research. As the number of critical technologies transported over networks increase, to minimise the delays and data loss, large transmission capacity with low-latency has become a prerequisite condition for accessing the fronthaul/backhaul and metro/core network segments such as in 5G & beyond networks. In addition, due to the need of wide range of technologies to access the networks, a flexible access over multiple protocols is a necessity. Hence, in the University of Bristol, Time Shared Optical Network (TSON) solution has been developed to address low-latency, large bandwidth and multi-protocol access needs of OTNs [1].

In the architecture proposed in [2], a single 100 Gb/s Ethernet connection between nodes and three 10 Gb/s Ethernet connections for end points are dedicated. TSON can aggregate and dis-aggregate an arbitrary number of 10 Gbps or less clients and multiplex them onto its TDM and WDM enabled 10 Gb/s or 100 Gb/s flows, as it can be seen in Fig.1. Also security could be dynamically adapted, by applying the encryptor to secure the metro/core and long-haul flows of the TSON, integrated TSON's resilient transport capabilities with the flexible security of a programmable hardware encryptor using a quantum key distribution system, please see [1, 3] for more details.

In this paper, we propose a mixed integer linear programming (MILP) to optimize network resources with TSON nodes,

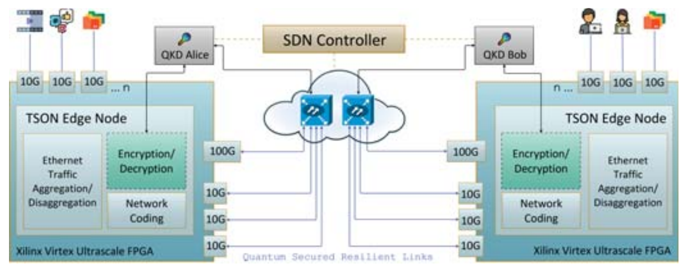

Fig. 1: Example of network configuration, testbed.

with multiple source-destination pairs and resilience based on configuration of Fig. 1. A comparison between two optimization objectives: i) minimize the maximum number of ports/fibers used for node or ii) minimize the total number of fibers in network is analyzed. The mathematical formulation is based on multi-fibers networks (could be adapted for multi-core, [4]) which is envisioned as the most appropriate operational scheme for TSON since it considers that different traffic can be established using different fibers and different configurations according to node requirements. This kind of design is at the heart of our understanding to take part, for example, with the 5GUK testbed network [5].

II. Scenario and Optimization

According to the work presented in [2], it has been demonstrated how network resilience can be achieved in optical domains by applying an Field Programmable Gate Array (FPGA)-based programmable encryptor to an environment hosting time-shared optical networks. It intended to provide a quantum secured and resilient transport access for applications sharing the same infrastructure.

As a result, it is possible to create environments with different and adjustable levels of security and resilience, which can be configured according to the quality of service agreed between clients and provider. There are two similar communication sides (source i and destination j), TSON edge node on the left acts as the server while the one on the right side holds the clients. Each board is connected to three clients through 10 Gbp/s (maximum) optical Ethernet connections. Also, there is one interface for the 100 Gb/s channel. They are connected to Optical Cross-Connectors (OXC) which interconnects all the entities in the system. The OXCs are configured by the SDN controller which has access to all agents. Inside the FPGA, there is the core responsible for traffic aggregation and dis-aggregation; the programmable encryptor/decryptor; and the Network Coding, i.e., where the resilient links are coded to have the ability of recovering the transmission after failures.

K. D. R. Assis is with the Federal University of Bahia (UFBA)-Brazil and University of Brsitol-UK, e-mail: karcius.assis@bristol.ac.uk

R. D. Oliveira, E. Arabul, R. Wang, R. Nejabati and D. Simeonidou are with University of Bristol-UK and R Almeida Jr is with UFPE.

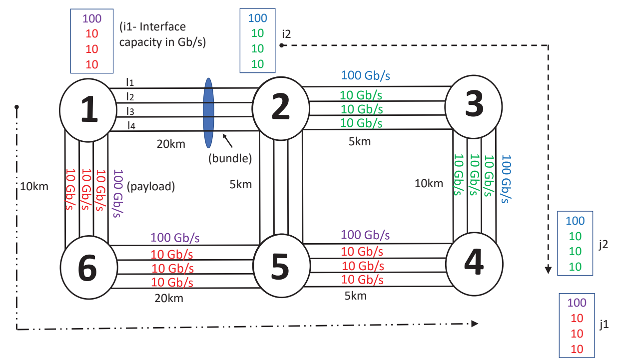

Fig. 2: Examples for two source-destination traffic transmission.

The connection between the two FPGAs is provided by four optical lanes. In addition, all lanes could be quantum secured according to the requirement. The SDN controller is a control plane's entity to orchestrate the software agents and forwarding hardware across the testbed. For evaluating the effectiveness of the proposed optimization strategy, the topology of Fig. 2 was considered. It has 4 fibers installed between 2 nodes and 4 traffic demands or reserved demands for a pair ij. For example, in Fig. 2, 3 lines with 10 Gb/s payload and a line with 100 Gb/s payload over the bundle. There are two demands, one starting from node 1 and ending on node 4 and another one starting from node 2 and ending on node 4. It is easy to see that if the demands from node 1 to node 4 is routed through bundles 1-2, 2-3 and 3-4, instead of 1-6, 6-5 and 5-4, additional fibers will be necessary on bundles 2-3 and 3-4. Another alternative is demand 1-4 use bundles 1-2, 2-5 and 5-4 or use some demands over a path and other demands by other paths. Therefore, the design of such network with several demands becomes a difficult optimization problem.

III. MILP Formulation

This section extends the research conducted on [2] (through simulation) with a novel MILP formulation to be applied for a physical substrate network with several demands taking advantages of a model for networks that can help to make decisions for a TSON designer. Therefore, we describe below the proposed MILP formulation for mapping traffic over a TSON taking into account practical and real testbed requirements.

A. Notation and Parameters

- m and n denote endpoints of a link bundle (group of fibers with the same origin and destination nodes) in the network.
- N_c denotes the total number of fibers that can be installed in any link bundle in the network.
- $c = 1 \dots N_c$ denotes the c-th fiber present in a specific $m - n$ link bundle in the network. In this paper each fiber in a link bundle uses a single wavelength.
- i and j denote respectively the source and destination nodes of a traffic demand in the network.
- p_k^{ij}: $k - th$ traffic demand (in $\mathrm{Gbit/s}$) between nodes i and j.
- χ: a big number.

B. Variables

- $P_{mn,c}^{ij,k}$: The amount of traffic from the k-th demand from node i to node j that is routed through the c-th fibre of link bundle i-j.
- $A_{mn,c}^{ij,k}$: A binary variable to indicate whether the k-th demand from node i to node j is routed ($A_{mn,c}^{ij,k} = 1$) or not ($A_{mn,c}^{ij,k} = 0$) through the c-th fibre of link bundle i-j.
- $g_{mn,c}$: A binary variable to indicate whether fiber c is used in link bundle mn.
- I_c: A binary variable to indicate whether the c-th fibre is used in at least one of the existing link bundles in the network.
- C_{mn}: Number of fibers used in link bundle mn.

C. Mathematical Formulation

- Objective Function 1:

$$Minimize : \sum_{c} cI_c \tag{1}$$

- Objective Function 2:

$$Minimize : \sum_{mn} C_{mn} \tag{2}$$

-Routing on physical topology (3), auxiliary constraint (4) and indicator of which fiber/port is used (5):

$$\sum_{n,c} P_{mn,c}^{ij,k} - \sum_{n,c} P_{nm,c}^{ij,k} = \begin{cases} p_k^{ij} & m = i \\ -p_k^{ij} & m = j \\ 0 & m \neq i,j \end{cases} \quad \forall ij,k,m \tag{3}$$

$$A_{mn,c}^{ij,k} \geq \frac{P_{mn,c}^{ij,k}}{\chi} \quad \forall ij,k,mn,c \tag{4}$$

$$I_c \geq \frac{\sum_{ij}\sum_{k}\sum_{mn} A_{mn,c}^{ij,k}}{\chi} \quad \forall c \tag{5}$$

-Traffic of a lightpath cannot be partitioned in the physical topology:

$$A_{mn,c}^{ij,k} + A_{ml,c}^{ij,k} \leq 1 \quad \forall i,j,k,m,c \quad n \neq l \tag{6}$$

-A single demand can be sent over any fiber in the network (7), indicator whether the c-th fiber of a link bundle is used; and (8) total number of fibers used over a link bundle (9).

$$\sum_{ij,k} A_{mn,c}^{ij,k} \leq 1 \quad \forall mn,c \tag{7}$$

$$\frac{\sum_{ij,k} A_{mn,c}^{ij,k}}{\chi} \leq g_{mn,c} \leq \sum_{ij,k} A_{mn,c}^{ij,k} \quad \forall mn,c \tag{8}$$

$$\sum_{c} g_{mn,c} = C_{mn} \quad \forall mn \tag{9}$$

IV. Simulations

For evaluating the effectiveness of the proposed optimization strategy, the topology of Fig. 2 was considered. We have assumed N_c=20 and k=4 traffic demands (100, 10, 10 and 10 Gb/s) for each source-destination node pairs. The IBM ILOG CPLEX v.11.0 was used on an Intel i7 3.6 GHz 32GB machine to solve the formulation.

Table 1 presents the results of the minimization of a) the maximum index of used ports over a node to attend the demands (obj_1); and b) the total number of used fibers in the network (obj_2). obj_1 works like a first fit strategy: the first port/fiber ($c = 1$) in a node has a lower weight than the second port ($c = 2$) for the function objective, which has lower weight than the third port, and so on. Therefore, the optimization tends to prioritize the use of lowest-index ports/fibers. On the other hand, with obj_2, the MILP formulation can use indistinctly any port, since the aim is to minimize their total number.

As it can be expected, the minimum number of used ports is achieved by obj_1, but not necessarily by obj_2. In this example, the minimum number of used ports rises from 16 to 20 when obj_2 is used instead of obj_1. On the other hand, the total number of used ports decreases from 214 to 200 if obj_2 is preferred against obj_1. This is related to the fact that obj_2, by prioritizing the use of the minimum number of fibers in the network, favors the use of shortest path routing instead of lowest-index ports, whereas the use of obj_1 strategy favors those paths with available lowest-index ports.

Because of the complexity of the problem, the strategy presented may be very time consuming, as can seen in the Table I. Therefore, heuristics will be necessary for large networks.

Fig. 3 shows the number of fibers used in each link bundle (C_{mn}) when the two optimization functions are used. As it can be seen, the number of interfaces/ports among all link bundles when obj_1 is used is between 14 and 16, against 10 and 17 with the use of obj_2. The effort of obj_1 in reducing the highest fiber index tends to equalize the number of fibers used per link bundle; differently from obj_2, which presents a higher diversity on the number of fibers per link bundle. Since obj_2 does not prioritize the lowest interface/port indexes, but instead the minimum number of used fibers in the network, it may leave some fragmentation in some fiber indexes' usage, which results in the maximum interface/port index of 20, as presented in Table 1.

Notice there was a perceived difference between the two optimization approaches, and the MILP can help the designer to choose the most appropriate solution for a real experiment, testbed or practical network, mainly when there are several demands and a limited budget. To achieve a balance between obj_1 and obj_2, a multi-objective formulation could be designed. It could operate by defining different costs for maximum interface index, network link bundle costs (as for avoiding those with higher risk of failure) or total number of used fibers. This would result in a problem of defining the best combination of costs. In further research, the use of the data reported here becomes means of our next demonstration, following the work made in [2]. Beside, multi-core optical networks and quantum channel constraints could be easily adapted by the constraints; making the model useful for experiments on different network scenarios.

TABLE I: Simulation results considering obj_1 and obj_2.

Simulation	$max(I_c)$	$\sum_{mn} C_{mn}$	run time
obj_1	16	214	3899 s
obj_2	20	200	78.3 s

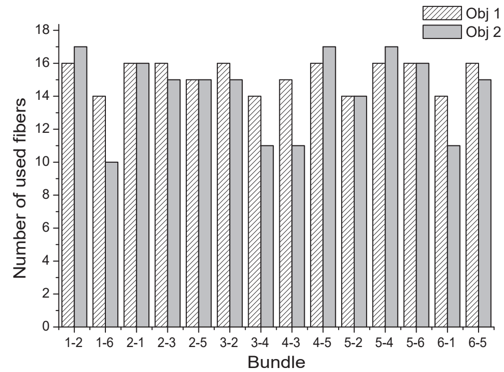

Fig. 3: Total number of fibers used for each link bundle for the two analysed approaches: objective function 1 and objective function 2.

V. Conclusion

In this paper, we propose a MILP formulation to be considered when designing networks with TSON nodes. The performance obtained in terms of two objective functions is a good benchmark for designer decisions. We can observe that obj_1 approach has about 20% better performance, in terms of the maximum number of used interfaces, in relation to obj_2. Furthermore, since obj_2 aims in minimizing the total number of used fibers in the network, it can also be useful in terms of cost for 5G testbed or real networks. The simulation approach to empirical research adopted for this study was based on trying to follow the experiment from [2]. However, the MILP offers some important attributes: 1) the availability of the number and kind of ports or fibers can be larger and therefore optimized by the proposed MILP; 2) the strategy can be adapted for multi-core optical networks by considering a bundle as a fiber and a fiber as a core; 3) quantum channel constraints could be adapted; making the model useful for experiments with different kinds of fibers. Further studies, which take these attributes into account, will need to be undertaken and they are our next steps.

*This study was financed in part by CAPES - Finance Code 001 and CNPq. This work also was funded by EU funded projects 5G-COMPLETE (871900) and UNIQORN (820474), EPSRC (grant ref. EP/T001011/1), also The Alan Turing Institute - UK.

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