Design of Logical Topology for IP over WDM Networks: Network Performance vs. Resource Utilization

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Abstract. We consider the problem of designing logical topologies for IP over WDM networks. One important feature of WDM networks is the reconfigurability when traffic demands change over time. However, if the network resource is not used efficiently, the reconfiguration can cause network disruption because new wavelength channels can be added only after deleting some working channels. Therefore, saving resource is an important issue while designing the logical topology. In this paper, we present a new approach to design logical topologies so that the network resource is used the most efficiently while the network performance is still guaranteed. The problem is formulated as a *mixed-integer linear programming* (MILP).

Keywords: WDM, optical network, lightpath, logical topology, optimization, mixed-integer linear programming (MILP).

1 Introduction

1.1 IP over WDM Networks

Currently optical networks employing wavelength division multiplexing (WDM) techniques are potential candidates for the next generation of wide area backbone networks. The reason for using optical technology in communication is its huge capacity (50THz) [8] that other technologies cannot offer. By using WDM technology, this capacity can be divided into many wavelength channels operating at electronic switches. In IP over WDM networks, IP packets are carried directly over WDM channels avoiding ATM or SDH as an intermediate layer. This approach leads to more efficient data transport network. A WDM network consists of WDM-aware nodes interconnected by fiber-optic links. The WDM-aware nodes include optical cross-connect swcitch (OXC) for routing an optical signal from one fiber to another without performing optoelectronic conversion, IP routers (transceivers) operating as electronic switches to multiplex and demultiplex data packets.

In IP over WDM networks, source and destination node can be connected by a wavelength channel, a so called lightpath. Once two nodes are connected by a lightpath, they become virtually neighbours, regardless of the physical connectivity between them. A set of those lightpaths creates a logical topology, which is implemented on top of a WDM network. This topology is normally not a full-mesh because there are not enough wavelengths and transceivers to create a lightpath between any node pair. Hence, some traffic needs to be switched electronically from one lightpath to another until it reaches the destination. This approach is called multi-hopping [8], which combines the best features of optics and electronics. At physical layer, optical nodes can be equipped with wavelength converters. With the help of wavelength converters, a lightpath can be set up with different wavelengths. Otherwise, a ligthpath can consist of only one single wavelength over a sequence of physical links. The existence of wavelength converters helps to reduce the number of wavelengths required. However, the use of wavelength converters is not cost-effective and may cause further complication due to the tuning delay of converters and other issues of converter placement [5].

The problem considered here is to design a logical topology and to embed it in a physical network for specific traffic demands with constraints on the number of transceivers and wavelengths. In this paper, we solve the logical topology design problem for multi-fiber WDM mesh networks without wavelength converters.

1.2 Related works

The logical topology design problem has been addressed earlier in several previous studies [1]-[7]. Most of those researches formulate the problem as a ***mixed-integer** linear programming*, which can optimally determine a logical topology subject to the number of transmitters, receivers and wavelength constraints, with one of the following objective functions: minimize link utilization [2], [3], minimize propagation delay [1], minimize average packet hop distance [4] and maximize offered load [1]. In [2], the constraints imposed by the physical topology and the limited number of wavelengths are ignored. In [1] and [4], the wavelength continuity is ignored by assuming that wavelength converters are available at routing nodes. Reference [3] overcomes the missing of wavelength continuity constraint in [1] and [4] by introducing an exact linear formulation for designing a logical topology without wavelength converters. Since those optimization problems are NP-complete, some heuristic algorithms were also proposed in the above-mentioned studies to solve the problem for large networks. Only [6] and [7] addressed the problem with taking resource utilization into account. [6] formulates the problem as a non-linear programming problem. [7] proposed a heuristic algorithm, so-called iterative algorithm, to reduce the number of lightpaths.

1.3 Problem statement

When designing the logical topologies with the objective of optimizing network performance, we observe that the resulting network tends to use all resources to set up as many lightpaths as possible. For example, in case of minimizing link utilization, many lightpaths are set up so that traffic can be spread over those lightpaths to reduce link load. In case of minimizing average hop-distance, the network tends to set up a full-mesh if possible to reduce hop distance. The consequence is that once the logical topology is set up, there will be no or very few remaining lightpaths for future use. In a static scenario where traffic rates never change the obtained solutions are optimal. However, in real networks, traffic demands between node pairs change considerably over time [11]. Therefore, reconfiguration of logical topologies is required to guarantee network performance. If all resources are used for a current topology, moving to a new topology will definitely cause disruption because no new lightpaths can be set up before deleting at least one existing lightpath. This problem becomes much more critical in optical networks due to the large bandwidth of a wavelength channel. A large amount of data will be disrupted when a lightpath is torn down. We therefore think that saving resources for further use in a reconfiguration process is as important as optimizing network performance. Hence, in this paper, we look at the logical topology design problem from two aspects: network performance and resource utilization. We propose a new optimization formulation with the objective of maximizing the number of remaining lightpaths while taking the network performance (link utilization) as a constraint. Our formulation results in a compromise of network performance and resource utilization.

The rest of this paper is organized as follows: Section 2 presents our MILP formulation of the problem. In section 3, an illustrative numerical example employing our formulation is discussed. Section 4 concludes our work.

2 Problem Formulation

We now formulate the problem of designing logical topologies as a mixed-integer linear programming (MILP), using the following notations:

- *s* and *d* denote source and destination nodes of a packet, respectively.
- *i* and *j* denote originating and terminating nodes of a lightpath, respectively.
- *m* and *n* denote endpoints of a physical link.
- $W = \{l\}$ where l denotes wavelengths.
- $R = \{r\}$: set of alternative routes, where *r* denotes route candidates for a lightpath in physical layer.

2.1 Given parameters

- Physical topology: $P = \{f_{mn}\}$, where f_{mn} indicates the number of fibers connecting node *m* and *n* and $f_{mn} = f_{nm}$.
- $d^{ij}_{mn,r}$ denote the existence of link *mn* in route *r* connecting node pair (*i*,*j*). If $d^{ij}_{mn,r} = 1$, then link *mn* belongs to route *r* between node pair (*i*,*j*) and $d^{ij}_{mn,r} = 0$ otherwise.
- Traffic matrix $H = \{h_{sd}\}$, where h_{sd} denotes the traffic rate between source-destination pair (*s*,*d*).
- T_i and R_i denote the number of transmitters and receivers respectively at node *i*.

- Link utilization indicator: $L_{\max}$ denotes the allowed maximum load in a lightpath. $L_{\max}$ should be lower than the capacity of a wavelength.

2.2 Variables

- Logical topology: $Y = \{y_{ij}\}$, where y_{ij} is the number of lightpaths between node *i* and *j*. A lightpath is not necessarily bidirectional. Hence, $y_{ij} \neq y_{ji}$.
- Traffic routing: t_{ij}^{sd} denotes the traffic between source-destination pair (*s*,*d*), routed through logical link *ij*.
- Physical routing: $p_{r,l}^{ij}$ denotes the number of times the wavelength l is assigned to route r connecting node-pair (*i*,*j*). In single-fiber networks, $p_{r,l}^{ij}$ becomes a binary variable.
- x_{ij} denotes the number of remaining lightpaths connecting node-pair (*i*,*j*).

2.3 Constraints

- Degree constraints:

$$\sum_j y_{ij} \leq T_i \qquad \forall i \tag{1}$$

$$\sum_i y_{ij} \leq R_j \qquad \forall j \tag{2}$$

The above constraints guarantee that the number of lightpaths originating from and terminating at a node is constrained by the number of transmitters and receivers at that node respectively.

- Traffic constraints on logical topology:

$$\sum_j t_{ij}^{sd} - \sum_j t_{ji}^{sd} = \begin{cases} h_{sd} & s = i \\ -h_{sd} & d = i \\ 0 & s \neq i, d \neq i \end{cases} \qquad \forall s, d \tag{3}$$

$$\sum_{sd} t_{ij}^{sd} \leq L_{\max} \cdot y_{ij} \qquad \forall i, j \tag{4}$$

Equation (3) is a multi-commodity flow equation representing the traffic routing on logical links. In this paper, we assume that the traffic can be bifurcated continuously. In real optical backbone networks, the traffic can be divided into non-bifurcated OC-x streams. Equation (4) ensures that the load on each logical link does not exceed a pre-determined maximum load $L_{\max}$.

Constraints on physical layer:

$$\sum_r \sum_l p_{r,l}^{ij} = y_{ij} \qquad \forall i, j \tag{5}$$

$$\sum_{ij}\sum_{r} p_{r,l}^{ij} \cdot d_{mn,r}^{ij} \leq f_{mn} \quad \forall m,n \tag{6}$$

Equation (5) ensures that all lightpaths of the logical topology can be routed in the physical topology. Constraint (6) ensures that the number of times a wavelength is used on a link is lower than or equal to the number of fibers on that link, so that a wavelength is used only once in each fiber. These constraints are created using link-path formulation [7], where all possible paths are known beforehand. Since the physical layer is given, we can easily pre-determine a set of alternative routes for any node pair. Using the link-path formulation significantly reduces the complexity of the problem, compared to the formulation in [3] and also overcomes the non-linearity of wavelength-continuity constraint in [1] and [4].

- Calculating possible remaining lightpaths:

To calculate the number of remaining lightpaths, we introduce the variable $z_{r,l}^{ij}$ representing the number of times the wavelength l is assigned to route r realizing a remaining lightpath between node-pair (***i,j***). In single-fiber network, $z_{r,l}^{ij}$ becomes a binary variable.

$$\sum_{j} x_{ij} \leq T_i - \sum_{j} y_{ij} \quad \forall i \tag{7}$$

$$\sum_{i} x_{ij} \leq R_j - \sum_{i} y_{ij} \quad \forall j \tag{8}$$

$$x_{ij} = \sum_{r,l} z_{r,l}^{ij} \qquad \forall i, j \tag{9}$$

$$\sum_{ij}\sum_{r} z_{r,l}^{ij} \cdot d_{mn,r}^{ij} \leq f_{mn} - \sum_{ij}\sum_{r} p_{r,l}^{ij} \cdot d_{mn,r}^{ij} \quad \forall mn \tag{10}$$

Equation (7) and (8) restrict the number of remaining lightpaths to the number of remaining transmitters and receivers respectively. Equation (9), similar to equation (5), ensures that all remaining lightpaths can be realized at the physical layer. Equation (10), ensures that the number of times a wavelength used on a link for remaining lightpaths does not exceed the remaining wavelength resource.

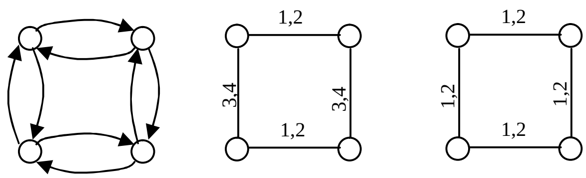
2.4 Objective

The objective of this formulation is to maximize the number of remaining lightpaths for further use.

$$\text{Max } \sum_{ij} x_{ij} \tag{11}$$

One may think that minimizing the number of lightpaths $\sum_{ij} y_{ij}$, which are set up in the logical topology, would also lead to efficient resource utilization. But this is not necessarily the case. Minimizing the number of lightpaths just leads to the saving of transceivers. It therefore only works if there is always free wavelengths available. In WDM networks with wavelength constraint, a lightpath can be set up only if there are free transceivers and wavelengths. Hence, minimizing the number of lightpaths is not enough to ensure the efficiency in resource utilization. The difference between those two objectives will be shown by a numerical example in Section III.

The objective above guarantees the maximum number of remaining lightpaths that can be set up simultaneously. However, we are also interested in maximizing the number of possibilities to set up a lightpath. In the future, we might need to set up a new lightpath, which is unknown beforehand, so increasing the possibilities to set up a lightpath can reduce the blocking probability. The following illustrative example will give a clear explanation.



(a) (b) (c)

Fig 1. An example for wavelength assignment

For a given logical topology in Fig 1(a), there are 2 different solutions for wavelength assignment in the physical topology as shown in Fig 1(b) and Fig 1(c). The numbers on each link show the wavelengths used on that link. We assume that there are 4 wavelengths in each fiber. In both solutions, we can set up additionally 8 different lightpaths simultaneously (2 lightpaths on each link). However, the solution in Fig 1(c) is preferred because in the absence of wavelength converters, it offers possibilities to set up a lightpath between any node-pair while the one in Fig 1(b) does not.

To maximize the number of possibilities to create a new lightpath, the objective function above needs a small change. We first assign an increasing cost to each wavelength $Cost(W) = \{a_l\}$, where W is the number of wavelengths multiplexed in each optical fiber, λ is the wavelength index, and $a_{l+1} > a_l$. The problem is then solved with a new objective function.

$$\text{Max} \quad \sum_{ij} x_{ij} - q \cdot \sum_{l} a_l \cdot \sum_{ij} \sum_{r} p^{ij}_{r,l} \cdot d^{ij}_{mn,r} \qquad (12)$$

where θ is chosen small enough so that the added term does not influence the main objective function in (11).

The above objective maximize the total number of remaining lightpaths and at the same time minimizes the total cost of wavelength on all fiber links used for designed logical topology. It ensures that wavelengths with lower costs will be assigned first. Hence, some wavelength can be saved. The new objective helps to reduce blocking probability in the absence of wavelength converters. The choice of those costs might affect the results. This will be shown in Section III.

3 Illustrative Numerical Examples

We use the single-fiber 6-node network in Fig 2 as a numerical example for this logical topology design problem. We assume that there are four transmitters and receivers at each node and four wavelengths multiplexed in a fiber. The wavelength capacity is 2.5Gbps. The traffic demand matrix, whose entry is chosen randomly from a uniform distribution in (0,1), is taken from [2] (Table 1). The unit for traffic rate is assumed to be Gbps. The wavelength cost is assumed to be $\{a_l\} = \{1, 1.2, 1.4, 1.6\}$.

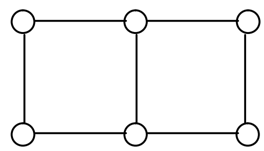


Fig 2. Six node network, physical topology.

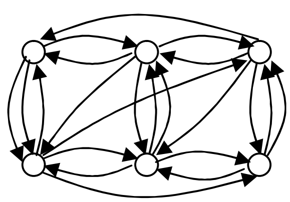
Table 1. Traffic matrix for 6-node network

0.000	0.537	0.524	0.710	0.803	0.974
0.391	0.000	0.203	0.234	0.141	0.831
0.060	0.453	0.000	0.645	0.204	0.106
0.508	0.660	0.494	0.000	0.426	0.682
0.480	0.174	0.522	0.879	0.000	0.241
0.950	0.406	0.175	0.656	0.193	0.000

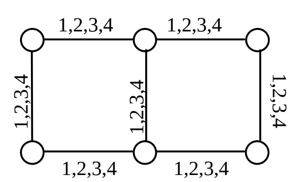
3.1 Trading resource consumption for link utilization

We compare our approach with the ones in previous studies, whose objective was to minimize the maximum link utilization.

In case of minimizing link utilization, we obtained the following topology. The numbers on each link represent wavelengths that are used on that link.



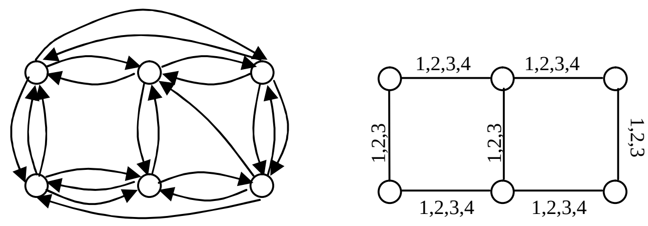
(a) Logical topology



(b) RWA in physical layer

Fig 3. Minimizing link utilization

The minimum link load is 1.105 Gbps, corresponding to the link utilization of 44.2%. If we take this link utilization as $L_{\max}$ and apply our formulation, we obtain the following logical topology:



(a) Logical topology (b) RWA in physical layer

Fig 4. Maximizing the number of remaining lightpaths

As can be seen in Fig 3b, all resources are used to minimize link utilization. However, in our solution, there are still free transceivers and wavelengths to set up three different lightpaths simultaneously. Thus, we achieve the same network performance but our solution outperforms the former in terms of resource utilization.

The question here is if it is necessary to use many resources to get that minimized link utilization, or it is better to accept higher link load level but save resources. In the following, we consider the results for different link loads.

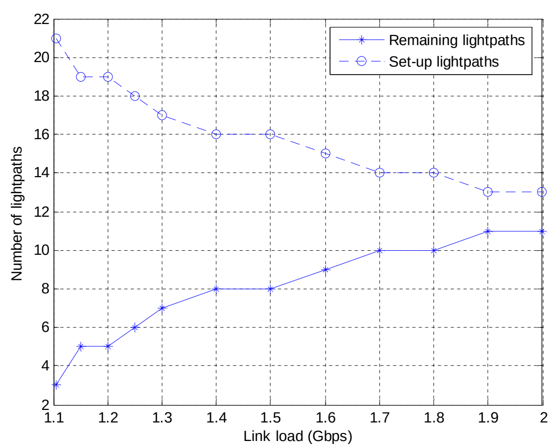
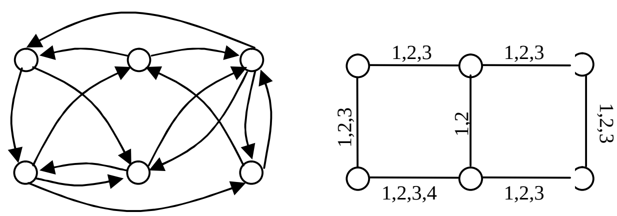


Fig 5. Results for different link loads

It is obvious that, the higher the link utilization is, the more resources we can save. Based on the traffic characteristic, we can choose appropriate link utilization for the network. If the traffic changes dramatically, choosing an appropriate link-utilization and hence saving some lightpaths for the reconfiguration would be needed. This will reduce the network disruption when the logical topology needs to be reconfigured.

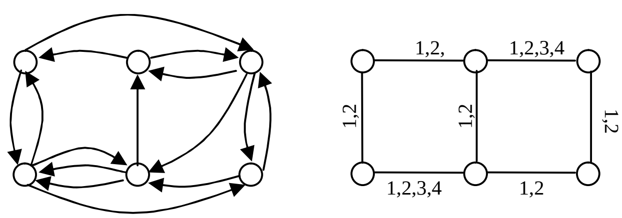
3.2 Maximizing the number of remaining lightpaths versus minimizing the number of lightpaths

One may argue that minimizing the number of lightpaths also leads to efficient resource utilization. We now compare this solution with our approach to see the difference. We assume that the maximum link load $L_{\max}$ is 1.6Gbps, corresponding to the link utilization of 64%. For the problem of minimizing the number of ligthpath, the constraint (13) is replaced by $\sum_{ij} y_{ij} = Obj1$, where *Obj1* is the minimized number of lightpaths. We obtained the following logical topologies (Fig 6 and 7) for two approaches.



(a) Logical topology (b) RWA on physical layer

Fig 6. Minimizing the number of lightpaths



(a) Logical topology (b) RWA on physical layer

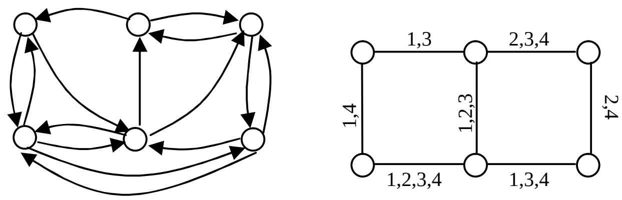
Fig 7. Maximize the number of remaining lightpaths

Minimizing the number of lightpaths results in 14 lightpaths, while our approach results in 15 lightpaths. However, as can be seen in Fig 6, there are only up to 7 remaining lightpaths that can be set up simultaneously in case the number of lightpaths is minimized, while in our solutions, there are up to 9 different lightpaths for further use. This is because the wavelength load (summation of wavelengths used on all fibers) in our solution is lower than the former. It is 18 in our solution, compared to 21 in the former one.

3.3 Effect of choosing wavelength cost

The choice of wavelength cost might affect the results in routing and wavelength assignment for lightpaths. We assume the link load to be 1.6 (64%), as in the previous section.

What follows is the topology without assigning costs to wavelengths, or in other words, all wavelengths are assigned the same cost.

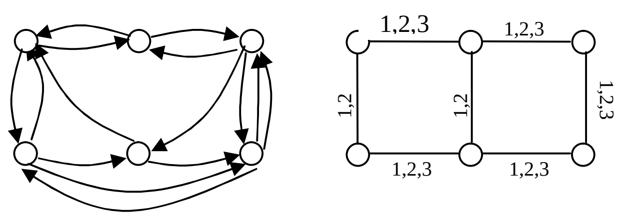


(a) Logical topology (b) RWA on physical layer

Fig 8. Wavelength cost is not assigned

Comparing this solution with the one in Fig 7, we see that the wavelength assignment is less efficient. Due to the wavelength continuity of a lightpath, many multi-hop lightpaths will be blocked if the wavelength assignment is done as in Fig 8. This shows the necessity to use the second step while designing the logical topology.

Now, we choose another cost set $\{C_i\} = \{1, 2, 4, 8\}$, and the result is as displayed in Fig 8.



(a) Logical topology (b) RWA on physical layer

Fig 9. Maximize the number of remaining lightpaths

In this solution, the wavelength load is more balanced than in Fig 7. However, the total wavelength load on all links is higher. It is 19 in this solution while 18 in the one of Fig 7. This is due to the big difference in wavelength costs, thus some lightpaths tend to use longer routes with lower wavelength cost, rather than to use short routes with high wavelength cost. So if we want to minimize the wavelength load on the network, it is necessary to choose the costs with just little difference. If the objective is to balance the wavelength load, a big difference in wavelength costs has to be preferred.

4 Conclusion

This paper proposed a new MILP formulation for the logical topology design problem in multi-fiber WDM mesh networks. This is divided into two steps with two objectives. The first step is to maximize the number of remaining lightpaths. The second step assigns costs to wavelengths and minimizes the total wavelength cost on all links while keeping the number of remaining lightpaths maximized. The network performance is guaranteed by adding a constraint that limits the link utilization. This approach outperforms current solutions in terms of resource utilization while the network performance of the logical topology is still maintained. It also shows the trade off of network performance and resource utilization. The formulation is shown to be NP-complete and therefore becomes intractable for large networks. Thus, for future works, a heuristic algorithm should be developed to solve real-size networks. A reconfiguration algorithm, which makes use of free lightpaths to move from an old topology to a new one without network disruption, is also a part of our current research.

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