

Power-Aware Logical Topology Optimization for IP-over-WDM Networks Based on Per-Lightpath Power Consumption Model

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ABSTRACT

This paper considers the problem of logical topology optimization in an IP-over-WDM network, with the objective to minimize the total power consumption used to support the given traffic demands. While there are several power consuming devices in a backbone WDM network, it is assumed that major power consumption occurs at IP router ports, which are termination points of optical connections or lightpaths. The logical topology optimization problem is first formulated as an integer linear programming (ILP) problem that is computationally difficult to solve. To focus on minimizing the power consumption, it is assumed that traffic routing is not limited by link capacities. Two systematic approaches to obtain a lower bound on the power consumption are considered, namely linear programming (LP) relaxation and Lagrangian relaxation. It is shown that both methods result in the same lower bound that corresponds to shortest path routing of traffic. A heuristic based on shortest path routing and pruning of unnecessary lightpaths is then evaluated using simulation results obtained from the heuristic in comparison to the baseline case in which the logical topology is taken to be the same as the physical topology. Finally, WDM networks that support mixed line rates are considered in order to further optimize the power consumption of IP-over-WDM networks in which transmission rates over different wavelength channels are not necessarily equal.

Keywords: IP-over-WDM Network, Power Efficiency, Logical Topology, ILP, LP Relaxation, Lagrangian Relaxation

1. INTRODUCTION

In recent years, power consumption in telecommunication networks has increased dramatically, and has become a critical issue in network planning and operations [1, 2]. For fixed network infrastructures, a large portion of power is consumed in backbone networks [3], which are expected to be based on wavelength division multiplexing (WDM) supporting the Internet

Protocol (IP), i.e., IP-over-WDM, with the transmission rate up to the order of 100 Gbps per wavelength channel.

In IP-over-WDM, most power is consumed by core IP routers [4]. This power consumption can be dramatically reduced through optical bypassing of traffic processing [4]. More specifically, to support optical bypass, each switching node contains an optical switch in addition to an IP router. Some traffic is switched entirely through the optical switch without being processed by the IP router. While optical bypass reduces the power consumption at IP routers, it requires the use of optical switches that also consume power. However, the power consumption of optical switches is expected to be much lower than that of IP routers when transmission rates are in the order of Gbps [5].

With optical bypass, IP routers are connected to one another with optical connections typically referred to as lightpaths, yielding a logical topology that may be different from the underlying physical topology.

The problem of logical topology optimization for WDM networks to support traffic demands has been much investigated [6–8], but power consumption was not the main issue for consideration. More recently, dynamic adjustment of the logical topology in response to traffic changes has received a lot of attention [9–11], but again power consumption was not the main focus. These existing investigations mostly focus on load balancing of traffic subject to the constraint on transmission capacities.

Motivated by the expectation that future WDM backbone networks may be limited more in terms of power consumption than transmission capacities [5], this paper investigates the problem of logical topology optimization in order to minimize the total power consumption without the limitation on transmission capacities. The assumption of no capacity limitation has also been adopted by some researchers working on logical topology optimization, e.g., [11]. In addition, it is assumed that power consumption is mainly due to IP routers, and that IP router ports may be put into the low-power idle mode when not utilized.

While this paper focuses mainly on the operations at the optical layer (i.e., WDM), it is worth pointing out that certain operations at the higher layer (i.e., IP) can also contribute to the reduction in power consumption in IP-over-WDM networks [1, 2]. For example, IP routers may adjust the packet sizes to reduce

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power consumption. As another example, IP routers may coordinate to set up virtual pipes to route packets of large data flows without having to process the headers of all individual packets. Therefore, it is also possible to employ a multi-layer approach in which different layers perform separate tasks simultaneously with a common goal of reducing power consumption.

The power-aware logical topology optimization problem is formulated in Section 2 as an integer linear programming (ILP) problem, which is computationally difficult to solve. Section 3 therefore applies standard approximation techniques based on linear programming (LP) relaxation and Lagrangian relaxation to find out lower bounds on the minimum power consumption. Mathematical analysis reveals that both techniques lead to shortest path routing as an approximation. However, since shortest path routing leads to a lower bound and does not necessarily lead to the minimum power consumption, a heuristic based on sequential pruning of unnecessary lightpaths is considered. Performance evaluation of the pruning-based heuristic is carried out in Section 4, which also quantifies the power savings in comparison to the baseline case with the logical topology being the same as the physical topology, i.e., without optical bypassing. Section 5 considers an extension of the work to be applicable for mixed-line-rate (MLR) WDM networks in which transmission rates of different wavelength channels are not necessarily equal. Finally, Section 6 summarizes key contributions and points out future research directions.

2. NETWORK MODEL AND PROBLEM STATEMENT

Consider an IP-over-WDM network in which source-destination (s-d) pairs have traffic demands that may not be integer multiples of the transmission rate of a single wavelength channel. For each node pair, there is a set of candidate paths for a logical link between them. Note that, for a specific node pair, the set of candidate paths can be empty if the physical distances of all candidate paths are beyond the optical reach, which is the maximum distance for reliable data transmissions. The traffic of each s-d pair is assumed static and known; this assumption is common for the design and optimization of backbone networks [6, 7].

The traffic of each s-d pair may be split into different substreams that are routed separately. Each substream may traverse multiple lightpaths, especially when there is no direct lightpath between the source and the destination. In addition, each active lightpath can carry traffic of multiple s-d pairs. In other words, active lightpaths support traffic multiplexing, which is also referred to as traffic grooming.

To describe the problem of logical topology optimization, the following notations are defined.

- \mathcal{N} : set of nodes

- \mathcal{S} : set of s-d pairs
- t^s : static traffic demand (in wavelength unit) for s-d pair s
- \mathcal{P} : set of candidate paths for logical links between all node pairs¹
- a^p : power consumption of an active lightpath on path p
- $\mathcal{P}_{(n,\cdot)}$: set of candidate paths (subset of \mathcal{P}) that start at node n
- $\mathcal{P}_{(\cdot,n)}$: set of candidate paths (subset of \mathcal{P}) that end at node n

The problem of logical topology optimization is to identify the values of the following decision variables. Note that \mathbb{R}^+ denotes the set of nonnegative real numbers, while \mathbb{Z}^+ denotes the set of nonnegative integers.

- $x^{p,s} \in \mathbb{R}^+$: traffic flow on path p for s-d pair s
- $y^p \in \mathbb{Z}^+$: number of lightpaths established (i.e., being active) on path p

The ILP problem for minimizing the total power consumption is formulated as follows.

$$\text{minimize } \sum_{p \in \mathcal{P}} a^p y^p \quad (1)$$

subject to

$$\begin{aligned} \forall s \in \mathcal{S}, \forall n \in \mathcal{N}, \quad & \sum_{p \in \mathcal{P}_{(\cdot,n)}} x^{p,s} - \sum_{p \in \mathcal{P}_{(n,\cdot)}} x^{p,s} \\ & = \begin{cases} -t^s, & n = \text{source of } s \\ t^s, & n = \text{destination of } s \\ 0, & \text{otherwise} \end{cases} \end{aligned} \quad (2)$$

$$\forall p \in \mathcal{P}, \quad \sum_{s \in \mathcal{S}} x^{p,s} \leq y^p \quad (3)$$

$$\forall p \in \mathcal{P}, \forall s \in \mathcal{S}, \quad x^{p,s} \in \mathbb{R}^+ \quad (4)$$

$$\forall p \in \mathcal{P}, \quad y^p \in \mathbb{Z}^+ \quad (5)$$

In particular, the objective in (1) is to minimize the cost function defined to be the total power consumed by active lightpaths. The flow conservation constraint is expressed in (2). The constraint in (3) prevents traffic from flowing on inactive lightpaths. Nonnegativity and integer constraints are expressed in (4) and (5).

In the above ILP problem, it is assumed that the total power consumption can be computed as the sum of per-lightpath power consumption. This assumption is consistent with the findings that power consumption in an IP-over-WDM backbone network is dominated by the power consumed by IP routers [4]. In addition, within an IP router, a large fraction of power is consumed by the transceiver ports, which are termination points of lightpaths [4]. In addition, the link capacity constraint is not taken into account in order to focus on minimizing power consumption. This assumption has previously been adopted by some researchers working on logical topology optimization, e.g., [11],

¹ As mentioned above, some node pair may not have any candidate path if all paths between them are longer than the optical reach.

and is made to explore the expected scenario in which WDM backbone networks have evolved to the point that their operations are limited mainly by their power consumption, and not by the capacity limitation.

3. LP RELAXATION AND LAGRANGIAN RELAXATION

Solving the ILP problem formulated in the previous section can be too time consuming since it involves solving the traffic grooming problem, which is known to be NP-complete [12]. While there are several heuristics proposed for the logical topology optimization problem, this section considers the use of two basic and systematic approximation techniques, namely LP relaxation and Lagrangian relaxation. Both techniques are known to provide a lower bound on the optimal cost, with Lagrangian relaxation yielding a tighter lower bound in general [13].

3.1 LP Relaxation for Lightpath Setup

Consider relaxing the integer constraint on the variables y^p in (5) into the following constraint.

$$\forall p \in \mathcal{P}, \quad y^p \in \mathbb{R}^+ \quad (6)$$

By inspection, without the integer constraint, each y^p must be set equal to $\sum_{s \in \mathcal{S}} x^{p,s}$ in constraint (3), or else the cost would increase further. It follows that the cost function can be rewritten as

$$\sum_{p \in \mathcal{P}} a^p y^p = \sum_{p \in \mathcal{P}} a^p \left(\sum_{s \in \mathcal{S}} x^{p,s} \right) = \sum_{s \in \mathcal{S}} \left(\sum_{p \in \mathcal{P}} a^p x^{p,s} \right). \quad (7)$$

To minimize the cost, each s-d pair s can minimize the quantity inside the brackets of the last expression in (7). Together with the flow conservation constraint, this minimization can be obtained by using shortest path routing over logical links (i.e., p 's), where the link distances are given by a^p 's.

In summary, LP relaxation yields an optimal solution corresponding to shortest path routing of traffic over candidate logical links. Such shortest path routing can be performed using standard techniques, e.g., Dijkstra algorithm.

3.2 Lagrangian Relaxation for Lightpath Setup

Let \mathbf{x} be a vector containing all $x^{p,s}$'s, and \mathbf{y} be a vector containing all y^p 's. Consider now relaxing constraint (3) using the Lagrangian relaxation approach [13]. Without this constraint, the optimization problem becomes an LP problem, which is computationally not difficult to solve. The associated Lagrangian can

be written as

$$\begin{aligned} L(\mathbf{x}, \mathbf{y}, \boldsymbol{\lambda}) &= \sum_{p \in \mathcal{P}} a^p y^p + \sum_{p \in \mathcal{P}} \lambda^p \left(\sum_{s \in \mathcal{S}} x^{p,s} - y^p \right) \\ &= \sum_{p \in \mathcal{P}} (a^p - \lambda^p) y^p + \sum_{s \in \mathcal{S}} \left(\sum_{p \in \mathcal{P}} \lambda^p x^{p,s} \right) \end{aligned} \quad (8)$$

where $\boldsymbol{\lambda}$ is a vector containing all dual variables λ^p 's.

Let \mathcal{X} be the set of \mathbf{x} 's that satisfy the flow conservation constraint (2) and the nonnegativity constraint (4), and \mathcal{Y} be the set of \mathbf{y} 's that satisfy the integer constraint (5). Accordingly, the dual function is

$$\begin{aligned} q(\boldsymbol{\lambda}) &= \min_{\mathbf{x} \in \mathcal{X}, \mathbf{y} \in \mathcal{Y}} L(\mathbf{x}, \mathbf{y}, \boldsymbol{\lambda}) \\ &= \min_{\mathbf{x} \in \mathcal{X}, \mathbf{y} \in \mathcal{Y}} \sum_{p \in \mathcal{P}} (a^p - \lambda^p) y^p + \sum_{s \in \mathcal{S}} \left(\sum_{p \in \mathcal{P}} \lambda^p x^{p,s} \right) \\ &= \min_{\mathbf{y} \in \mathcal{Y}} \sum_{p \in \mathcal{P}} (a^p - \lambda^p) y^p + \min_{\mathbf{x} \in \mathcal{X}} \sum_{s \in \mathcal{S}} \left(\sum_{p \in \mathcal{P}} \lambda^p x^{p,s} \right). \end{aligned} \quad (9)$$

The two terms in (9) can be separately computed. Consider the first term. If $\lambda^p > a^p$ for any $p \in \mathcal{P}$, then $q(\boldsymbol{\lambda}) = -\infty$ since y^p can be set arbitrarily large. In addition, when $\lambda^p \leq a^p$ for all $p \in \mathcal{P}$, the term is minimized by setting all y^p 's equal to 0. It follows that the domain set of $q(\boldsymbol{\lambda})$ is $\{\lambda^p | 0 \leq \lambda^p \leq a^p \text{ for all } p \in \mathcal{P}\}$, and the first term is equal to 0 in this domain.

The second term in (9) can be minimized using shortest path routing of traffic through logical links, where the link distances are given by λ^p 's. It follows that $q(\boldsymbol{\lambda})$ is equal to the sum $\sum_{s \in \mathcal{S}} \left(\sum_{p \in \mathcal{P}} \lambda^p x^{p,s} \right)$ associated with shortest path routing.

Consider now the dual problem

$$\text{maximize } q(\boldsymbol{\lambda}) \quad (10)$$

$$\text{subject to } \forall p \in \mathcal{P}, \quad 0 \leq \lambda^p \leq a^p \quad (11)$$

Since $\sum_{s \in \mathcal{S}} \left(\sum_{p \in \mathcal{P}} \lambda^p x^{p,s} \right)$ increases with each λ^p , it follows that the dual optimal cost q^* is obtained by setting $\lambda^p = a^p$ for all $p \in \mathcal{P}$. Consequently, q^* is equal to the sum $\sum_{s \in \mathcal{S}} \left(\sum_{p \in \mathcal{P}} a^p x^{p,s} \right)$ associated with shortest path routing, where the link distances are given by a^p 's.

In summary, Lagrangian relaxation yields the same lower bound as obtained from LP relaxation, as specified formally below. Accordingly, in the remaining parts of this paper, each technique is referred to simply as relaxation.

Theorem 1: For the power-aware logical topology optimization problem described in Section 2, LP relaxation and Lagrangian relaxation (of active lightpath constraints) yield the same lower bound, which corresponds to shortest path routing of traffic over logical links whose link distances are given by a^p 's.

3.3 Integer Rounding for Integral Numbers of Lightpaths

When followed by integer rounding to obtain integral numbers of active lightpaths, the corresponding optimal cost is $\sum_{p \in \mathcal{P}} a^p \lceil y^p \rceil$, where y^p is the traffic load on path p from shortest path routing. However, this process of integer rounding is not always optimal, as illustrated by the following simple example.

Example 1: This simple example illustrates a scenario in which relaxation followed by integer rounding is not optimal. Consider a 3-node bidirectional ring network as shown in Fig. 1 together with traffic demands to be supported. Assume that $a^p = 1$ for all $p \in \mathcal{P}$.

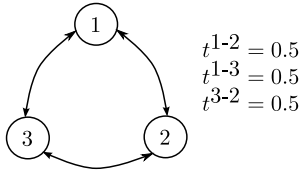


Fig.1: 3-node bidirectional ring network together with traffic demands

Relaxation (i.e., shortest path routing) followed by integer rounding yields 3 lightpaths: $1 \rightarrow 2$, $1 \rightarrow 3$, and $3 \rightarrow 2$. The traffic flows on them are all equal to 0.5. The corresponding cost is 3.

However, it can be seen that the minimum cost is 2 since the traffic for s-d pair 1-2 can be supported on lightpaths $1 \rightarrow 3$ and $3 \rightarrow 2$. ■

3.4 Pruning-Based Heuristic for Lightpath Setup

Since relaxation followed by integer rounding is not efficient even for the simple scenario in Example 1, this section describes an improvement using a local search technique based on sequential pruning of lightpaths as described below.

Algorithm 1: The procedure for sequential pruning of lightpaths is as follows.

1. Apply shortest path routing to all traffic demands over the set of logical links, where the link distances are given by a^p 's. Based on the results, record the traffic loads on the logical links, i.e., lightpaths.
2. Lightpaths are considered one by one in the increasing order of traffic loads.
3. For each considered lightpath, the traffic routing problem is resolved after removing the considered lightpath. More specifically, the routing problem is the LP problem in Section 2, where y^p 's are viewed as given. If the LP problem is feasible, then the considered lightpath is removed. Otherwise, the considered lightpath is put back into the logical topology.
4. The above step is repeated until all lightpaths are considered.

It is straightforward to verify that this pruning technique yields the minimum cost in Example 1.

More general performance evaluation results are presented in the next section.

4. PERFORMANCE OF PRUNING-BASED HEURISTIC

In this section, the performance of the pruning-based heuristic is evaluated and compared with the results from using the physical topology as the logical topology, i.e., without optical bypass. The considered physical network topologies are the 8-node topology shown in Fig. 2 and the well known COST 239 topology shown in Fig. 3.² In each figure, link labels denote the physical distances between adjacent nodes (in km).

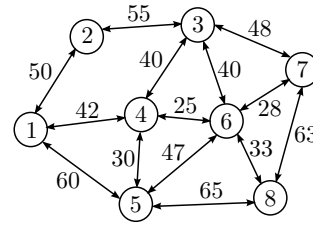


Fig.2: 8-node topology for performance evaluation of the pruning-based heuristic

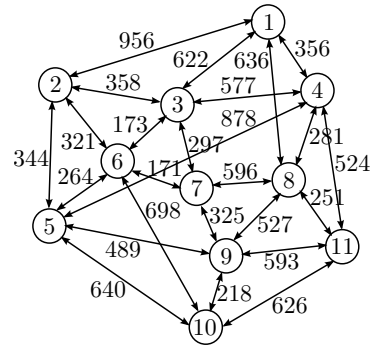


Fig.3: COST 239 topology for performance evaluation of the pruning-based heuristic

Table 1 lists the simulation parameters used to evaluate the pruning-based heuristic. Between the two considered network topologies, the same simulation parameters are used, except for the number of s-d pairs, i.e., $|\mathcal{S}|$, which is set to 40 (instead of 30) for the COST 239 topology since it is larger than the 8-node topology.

For each node pair, assume that a logical link or lightpath between them, if active, is constructed using shortest path routing based on the physical distances (in km). Note that only subwavelength traffic demands are considered in the simulation. With traffic demands above the rate of a wavelength, the integral parts can be supported on dedicated lightpaths in a straightforward fashion without traffic grooming.

² The latter topology is used in the COST 239 project, which investigates the operations of an optical backbone network connecting major cities of Europe [15].

Table 1: Simulation parameters for performance evaluation of the pruning-based heuristic

Parameter	Notation	Value
No. of s-d pairs	$ \mathcal{S} $	30 (8-node) 40 (COST 239)
Choice of s-d pairs	–	uniform random
Traffic demands	t^s	uniform random over $[0, \alpha]$
Traffic parameter	α	0.2, 0.4, 0.6, 0.8, 1
No. of simulation runs per data point	–	5
Power consumption per lightpath	a^p	1

Simulation is carried out using the Python software with relevant mathematical packages including PuLP [14] for solving ILP problems.

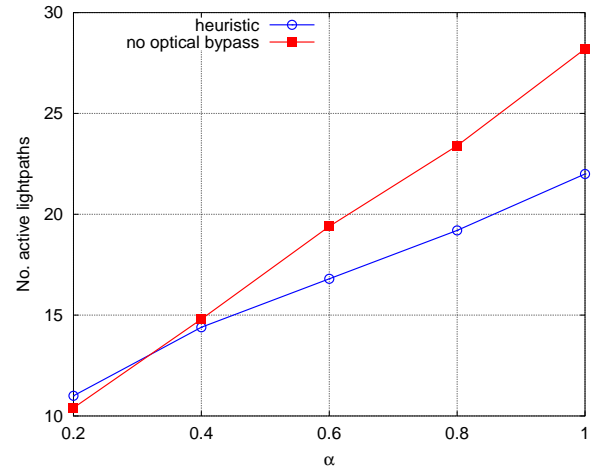
4.1 Numerical Results for the 8-Node Topology

Fig. 4 compares the average total power consumption, which is equivalent to the number of active lightpaths when $a^p = 1$ for all $p \in \mathcal{P}$, between the pruning-based heuristic and the baseline case without optical bypass. For the baseline case, the ILP problem of Section 2 is solved after setting $\mathcal{P} = \mathcal{L}$, i.e., the logical links being the same as the physical links.

It can be observed that the simple heuristic can lead to significant power savings when the traffic demands increase to be comparable to the transmission rate of a wavelength channel, i.e., α close to 1. This increase in power savings with the parameter α is related to the fact that there are more traffic grooming opportunities when there is more traffic in the network, yielding more reduction in the number of lightpaths.

Based on the same results as used to produce Fig. 4, the average lengths (in number of hops based on the physical topology) of active lightpaths are 1.67, 1.67, 1.65, 1.62, 1.65 for $\alpha = 0.2, 0.4, 0.6, 0.8, 1$ respectively. There is no noticeable trend in terms of the relationship between the lightpath length and the traffic parameter α . Note that the average lightpath length in \mathcal{P} is 1.64.

Table 2 compares the run time to obtain solutions for the pruning-based heuristic and for solving the ILP problem in Section 2. It can be observed that the pruning-based heuristic can greatly reduce the run time while providing reasonably close to the minimum number of lightpaths. It should be noted that the average run time of solving the ILP problem exactly is greater than 2 hour.

**Fig. 4:** Numbers of lightpaths from the pruning-based heuristic and from the baseline case without optical bypass for the 8-node topology in Fig. 2**Table 2:** Run time comparison between ILP and the pruning-based heuristic (with $\alpha = 0.8$)

Traffic pattern	Run time (s)		No. lightpaths	
	ILP	heuristic	ILP	heuristic
1	10891.5	13.11	18	19
2	6668.2	13.35	20	21
3	2914.7	12.88	19	19
4	17022.8	13.25	17	19
5	6558.9	12.89	18	18

4.2 Numerical Results for the COST 239 Topology

In this larger network scenario, the ILP approach is too time consuming even for the baseline case with no optical bypass. Hence, the same pruning approach is used for the baseline case without optical bypass. In particular, the procedure as outlined in Section 3. D can be used starting with \mathcal{P} set equal to \mathcal{L} .

Fig. 5 compares the average total power consumption, which is equivalent to the number of active lightpaths, between the pruning-based heuristic and the baseline case without optical bypass. The numerical results in Fig. 5 shows the same trend as in Fig. 4, with the power savings being more significant as the traffic parameter α increases. Note that, with 40 instead of 30 s-d pairs, the amount of traffic supported by the COST 239 topology is larger than for the 8-node topology. Hence, in comparing Fig. 4 to Fig. 5, the amount of power savings is higher for the COST 239 topology.

5. EXTENSION TO WDM NETWORKS WITH MIXED LINE RATES

This section discusses an extension of logical topology optimization to IP-over-WDM networks with

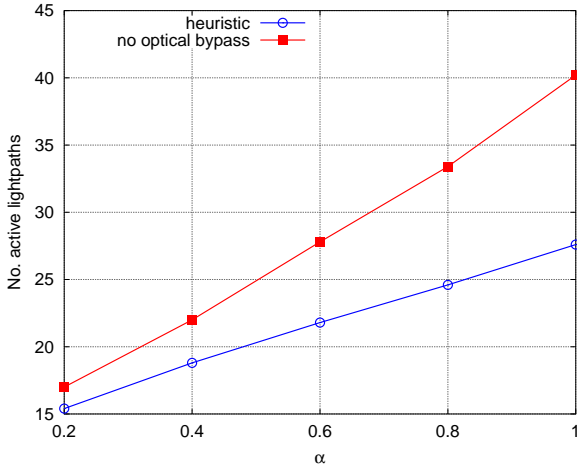


Fig. 5: Numbers of lightpaths from the pruning-based heuristic and from the baseline case without optical bypass for the COST 239 topology in Fig. 3. For both cases, pruning of lightpaths is applied, starting from the smallest traffic load to the highest traffic load based on shortest path routing.

mixed line rates, which are referred to as mixed-line-rate (MLR) networks [17]. In a MLR network, each wavelength channel can support one of several possible transmission rates, e.g., 10, 40, or 100 Gbps. It is expected that switching from one transmission rate to another only requires changing transponders at both ends of the corresponding lightpath. However, the optical reach typically decreases with the transmission rate. Hence, some candidate path for a logical link may be feasible for one rate, but not so for a higher rate.

To modify the ILP problem formulation in Section 2, let \mathcal{R} denote the set of transmission rates available in an MLR network. To accommodate different transmission rates, the decision variables of the form y^p and $x^{p,s}$ are modified as follows, where $r \in \mathcal{R}$ in each case.

- $x_r^{p,s} \in \mathbb{R}^+$: traffic flow (in traffic unit) on path p for s-d pair s on wavelength channel(s) with transmission rate r
- $y_r^p \in \mathbb{Z}^+$: number of lightpaths established (i.e., being active) on path p with transmission rate r

Accordingly, the network parameters are defined as follows.

- a_r^p : power consumption of an active lightpath on path p at transmission rate r , assumed equal to ∞ when the distance of path p is longer than the optical reach of rate r ³
- b_r : value (in traffic unit) of transmission rate r

Different from the ILP formulation in Section 2, it is no longer possible to use “wavelength unit” for the

³ Under this assumption, only one set of paths, i.e., \mathcal{P} , is sufficient; we do not need distinct sets of paths, i.e., \mathcal{P}_r for each $r \in \mathcal{R}$.

traffic amount since a wavelength can support one of several transmission rates in \mathcal{R} . This is why the “traffic unit” is used instead, with b_r ’s defined as additional parameters. For example, if 10 Gbps is used as a traffic unit, then a MLR network supporting transmission rates 10, 40, and 100 Gbps, will have $\mathcal{R} = \{1, 2, 3\}$ with $b_1 = 1, b_2 = 4$, and $b_3 = 10$.

5.1 ILP Problem Formulation and Relaxation

The ILP problem for minimizing the total power consumption in a MLR network is formulated as follows.

$$\text{minimize } \sum_{r \in \mathcal{R}} \sum_{p \in \mathcal{P}} a_r^p y_r^p \quad (12)$$

subject to

$$\begin{aligned} \forall s \in \mathcal{S}, \forall n \in \mathcal{N}, \quad & \sum_{r \in \mathcal{R}} \sum_{p \in \mathcal{P}(s,n)} x_r^{p,s} - \sum_{r \in \mathcal{R}} \sum_{p \in \mathcal{P}(n,s)} x_r^{p,s} \\ & = \begin{cases} -t^s, & n = \text{source of } s \\ t^s, & n = \text{destination of } s \\ 0, & \text{otherwise} \end{cases} \end{aligned} \quad (13)$$

$$\forall r \in \mathcal{R}, \forall p \in \mathcal{P}, \quad \sum_{s \in \mathcal{S}} x_r^{p,s} \leq b_r y_r^p \quad (14)$$

$$\forall r \in \mathcal{R}, \forall p \in \mathcal{P}, \forall s \in \mathcal{S}, \quad x_r^{p,s} \in \mathbb{R}^+ \quad (15)$$

$$\forall r \in \mathcal{R}, \forall p \in \mathcal{P}, \quad y_r^p \in \mathbb{Z}^+ \quad (16)$$

In particular, the objective in (12) is to minimize the cost function defined to be the total power consumed by active lightpaths. The flow conservation constraint is expressed in (13). The constraint in (14) prevents traffic from flowing on inactive lightpaths for each rate r . Nonnegativity and integer constraints are expressed in (15) and (16).

Using the arguments similar to Section 3, it can be shown that both LP relaxation and Lagrangian relaxation lead to the same lower bound, as indicated formally below. The detailed proof is a straightforward extension, and is therefore omitted.

Theorem 2: For the power-aware logical topology optimization problem modified for MLR networks, LP relaxation and Lagrangian relaxation (of active lightpath constraints) yield the same lower bound, which corresponds to shortest path routing of traffic over logical links, where the distance of path p is given by $\min_{r \in \mathcal{R}} a_r^p / b_r$.

It is worth noting that $\min_{r \in \mathcal{R}} a_r^p / b_r$ will typically correspond to the maximum line rate that does not exceed the optical reach. This is because we expect the power consumption (i.e., a_r^p) to increase with a smaller multiplicative factor than the line rate (i.e., b_r). For example, in [16], increasing from 10 Gbps to 40 and to 100 Gbps correspond to increasing the power consumption from 1 unit to 2.5 and to 4 unit respectively.

Similar to the case without MLR, solving the ILP problem exactly can be done only for small networks

due to high computational complexity. In addition, relaxation followed by rounding may not be optimal; Example 1 is still a valid example of suboptimality. Therefore, a heuristic is developed in the next section.

5.2 Modified Pruning-Based Heuristic

To account for mixed line rates, Algorithm 1 is modified in this section. Roughly speaking, between active s-d pairs, direct logical links are first set up at the maximum line rates subject to the optical reaches. Then, logical links are ranked according to the normalized traffic loads, which are the traffic loads divided by the line rates. Pruning is then applied to logical links according to the increasing order of the normalized traffic loads.

Algorithm 2: The modified pruning-based heuristic for MLR networks proceeds as follows.

1. Apply shortest path routing to all traffic demands over the set of logical links, where the link distances are given by $a_{r(p)}^p/b_{r(p)}$'s, where $r(p) = \arg \min_{r \in \mathcal{R}} a_r^p/b_r$. Based on the results, record the normalized traffic loads on the logical links (i.e., lightpaths), which are computed by dividing the link loads by the corresponding line rates $r(p)$'s.
2. Lightpaths are considered one by one in the increasing order of normalized traffic loads.
3. For each considered lightpath, the traffic routing problem is resolved after removing the considered lightpath. More specifically, the routing problem is the LP problem in Section 5.1 where y_r^p 's are viewed as given. If the LP problem is feasible, then the considered lightpath is removed. Otherwise, the considered lightpath is put back into the logical topology.
4. The above step is repeated until all lightpaths are considered.
5. Finally, each logical link is examined for line rate reduction, if possible. This is to avoid unnecessarily high power consumption.

Note that, compared to Algorithm 1, the final step is added to remove unnecessarily high line rates from some logical links. The performances of this modified algorithm are demonstrated in the next section.

5.3 Numerical Results for MLR Networks

Simulation experiments are carried out to evaluate the performances of the modified pruning-based heuristic for MLR networks. The same two network topologies in Fig. 2 and 3 are considered. Table 3 lists the parameters used in simulation experiments.

For comparison, network with fixed line rates, referred to as single line rate (SLR) networks, are considered with all logical links operating at 10 Gbps, which is adopted as 1 traffic unit. For SLR networks, the previous pruning-based heuristic can be applied. In comparison to Section 4, the range of traffic parameter α is increased beyond 1 so that higher line rates become reasonable options.

Table 3: Simulation parameters for performance evaluation of the modified pruning-based heuristic for MLR networks; 1 unit of line rate corresponds to 10 Gbps; 1 unit of power consumption corresponds to power consumption of a 10-Gbps lightpath; relative power consumptions and optical reaches for MLR networks are based on [16]

Parameter	Notation	Value
No. of s-d pairs	$ \mathcal{S} $	30 (8-node) 40 (COST 239)
Choice of s-d pairs	–	uniform random
Traffic demands	t^s	uniform random over $[0, \alpha]$
Traffic parameter	α	1, 2, 3, 4, 5
No. of simulation runs per data point	–	5
Line rate (normalized)	b_r	1, 4, 10
Power consumption per lightpath (normalized)	a_r^p	1, 2.4, 4
Optical reach (km)	–	1600, 1100, 940

Fig. 6 compares the normalized power consumption between MLR and SLR networks with the 8-node topology in Fig. 2. It can be seen that, as traffic loads increase, MLR can offer significant power savings. This is because higher line rates offer the volume discount effects in terms of the power consumption per traffic unit. However, it should be noted that, at low traffic loads, MLR may be not attractive.

Fig. 7 shows the same information as Fig. 6 but for the COST 239 topology in Fig. 3. Recall that the number of active s-d pairs for the COST 239 topology is higher than for the 8-node topology (i.e., 40 instead of 30). Thus, higher power consumptions are observed. Nevertheless, the same attractiveness of MLR can be observed for high traffic loads.

6. CONCLUSION

This paper considers the problem of logical topology selection in order to minimize the total power consumption based on the per-lightpath power consumption model. Link capacity constraints are ignored in order to focus on power minimization in an expected scenario where transmission powers are the main limitation instead of transmission capacities. It is shown that two basic systematic approximation techniques, namely LP relaxation and Lagrangian relaxation, lead to shortest path routing of traffic over logical links.

A heuristic based on shortest path routing followed by pruning of unnecessary lightpaths is then evaluated to quantify the amount of power savings obtained in

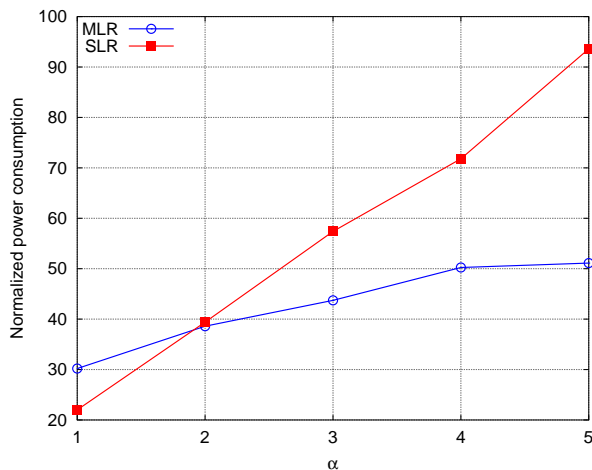


Fig. 6: Normalized power consumption from the pruning-based heuristic for SLR and MLR networks with the 8-node topology in Fig. 2

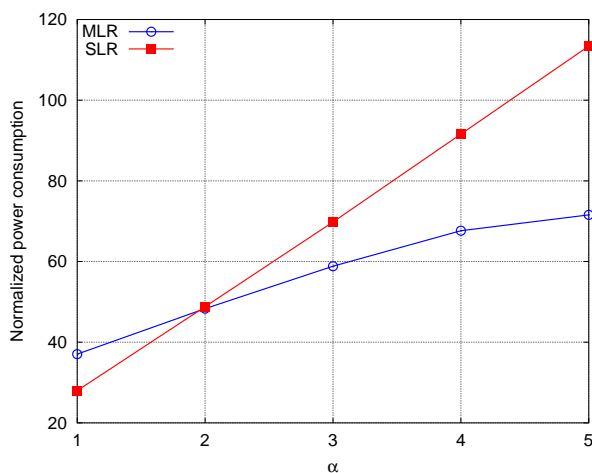


Fig. 7: Normalized power consumption from the pruning-based heuristic for SLR and MLR networks with the COST 239 topology in Fig. 3

comparison to the baseline case without optical bypass. It can be observed that the simple heuristic can provide nonnegligible power savings when traffic demands are high compared to the transmission rate of a wavelength channel.

Finally, the pruning-based heuristic is extended to take into account the possibility of using different transmission line rates in MLR networks. Numerical results indicate that, compared to networks with fixed line rate, power savings can be obtained from using MLR at traffic loads beyond the fixed line rate.

Future research directions include incorporating other power consumption models into the framework, including power consumed by optical amplifiers and optical switches.

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