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Energy Aware Scheduling and Routing of Periodic Lightpath Demands in Optical Grid Networks

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Abstract

Optical grid networks provide an ideal infrastructure to support large-scale data intensive applications and interconnection of data centers. The power consumption of communications equipment for such networks has been increasing steadily over the past decade and energy efficient routing schemes and traffic models can be utilized to reduce the energy consumption. In many applications it is possible to select the destination node from a set of possible destinations, which have the required computing/storage resources. This is known as *anycasting*. We propose a novel formulation that exploits knowledge of demand holding times and the flexibility of anycast routing to optimally schedule demands (in time) and route them in order to minimize overall network energy consumption. Our simulation results demonstrate that the proposed approach can lead to significant reductions in energy consumption, compared to traditional routing schemes.

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Keywords: Energy-aware routing; scheduled traffic; optical-grid networks; demand holding times; anycasting.

1. Introduction

Recent studies have shown that the energy consumption can become the bottleneck for the high speed data communication [1,2] in today's networks. Efficient routing schemes and resource allocation both in optical and electrical domain can be used to help mitigate this problem [3]. A transparent IP-over-WDM (wavelength division multiplexing) network can be utilized to allow traffic to optically bypass the electronic components, e.g. IP routers and switches, which typically consumes more power than the corresponding optical equipment. In recent years various research works have been published in the field of energy efficient WDM networks. A number of different approaches have been proposed including switching off or slowing down unused network elements [4], reducing electrical-optical-electrical

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(E-O-E) conversions[5], putting selected network components in sleep mode[6], and using intelligent traffic grooming techniques[7,8]. For many types of applications in optical grid networks, the user may not care exactly where their job is being processed. This allows the routing algorithms the flexibility of choosing a suitable processing (destination) node for a given task, such that network resources can be utilized as efficiently as possible. This is known as the principle of anycast routing[9]. A number of recent papers have shown how *anycast* routing can be used for minimizing the overall energy consumption in optical networks[10,11,12]. However, these papers mostly deal with the static[13,14] or dynamic[15,16] traffic models.

In this paper, we address the problem of energy efficient routing of traffic demands, under the sliding *scheduled traffic model* (STM)[17]. Rather than using the traditional unicast routing, our proposed approach uses the anycast principle to select the most suitable destination for a given demand. Furthermore, we present a novel approach that jointly routes and schedules demands in time. We have developed a new integer linear program (ILP) formulation to optimally solve this integrated routing and scheduling problem. We consider power consumption at both network nodes (e.g. in IP routers, optical switches) and along fiber links.

The rest of the paper is organized as follows: in Section 2 we present the literature review. In Section 3 we formulate our energy-aware scheduling and routing problem. We discuss our simulation results in Section 4 and conclude this study in Section 5.

2. Review of Energy-Aware Allocation Scheme

It has been predicted that "energy consumption rather than the cost of the component equipment may eventually become the barrier to continued growth"[1] for today's core/transport networks. Consequently, energy efficiency of core wavelength division multiplexing (WDM) networks has received significant research attention in the last few years[18,6]. A number of techniques for energy-efficient resource allocation with unicast routing in WDM optical networks have been reported in the literature. More recently, energy aware approaches (both heuristics and optimal formulations) using anycast routing has been considered in[18,10,12].

In[4], the goal is to find routes in the topology in such a way that it reduces the overall power consumption, by switching of unused network elements. In[18], the authors propose ILP formulations and heuristics that can reduce power consumption by selective switching off optical links. In[6], the authors introduce a model where each node stores two predetermined thresholds that trigger the node switching between sleep and active modes, depending on traffic load. One drawback of this model is it can drop lightpath requests due to isolated nodes. All the above papers consider either the static traffic model, where the traffic demands are set up on a permanent or semi-permanent basis, or the dynamic traffic model, where connection requests arrive randomly and are allocated on-demand as they arrive. Finally, in[12] the authors address the energy-aware anycast routing problem for the fixed window scheduled traffic model[19], where the traffic demands are periodic, with specified start and end times that are known beforehand. Our approach differs from the existing works in that we consider the *sliding* scheduled traffic model[17 20] and investigate if adding some flexibility in terms of the demand start and end times can help to further reduce the overall network energy consumption.

3. Energy aware routing and scheduling of SLDs

Our formulation takes as input a physical topology $G[N, E]$; here N is the set of nodes and E is the set of fiber links, where each fiber can accommodate a set of K WDM channels. We are also given a set P of scheduled lightpath demands (SLDs) and the entire time duration is divided into m_{max} intervals, numbered $m = 1, 2, 3..m_{max}$. Each demand $p \in P$ is specified as a tuple (s_p, D_p, α_p, ω_p, τ_p). A demand p has a specified duration τ_p, and can be scheduled any time within a larger window (α_p, ω_p), such that the demand can only start after α_p, and must be completed before ω_p. Clearly $(\omega_p - \alpha_p + 1) \geq \tau_p$. Here s_p is the source node for the SLD and D_p is a set of potential destination nodes, from which the routing algorithm will choose the most suitable one.

The total power consumption of an active IP router (P_{IP}) and an optical switch (P_{SW}) are shown in (1) and (2) respectively.

$$P_{IP} = C^s_{IP} + C^d_{IP} \cdot t_{IP} \quad (1)$$

$$P_{SW} = C^s_{SW} + C^d_{SW} \cdot t_\lambda \tag{2}$$

In both cases, the first term denotes the *static* component of the power consumption for simply turning the device ON or making it *active*. The second term is the load dependent portion of the power consumption and increases with the amount of traffic t_{IP} (t_λ) flowing through the IP router (optical switch). Finally, C^e_{link}, the power consumption of an active fiber link e is shown in (3). The value of C^e_{link} is determined by the number of inline amplifiers plus the pre and post amplifiers for each link, and can be calculated beforehand. The power consumption rates of different components are taken from[21].

$$C^e_{link} = C_{pre} + n_e \cdot C_{ILA} + C_{post} \tag{3}$$

We present integer linear program (ILP) formulation that takes into consideration the energy at network nodes (including electronic routing and optical switching) and along the fibers and minimizes energy consumption by selecting a suitable destination, route, wavelength and start time for each demand. The idea is to establish the set of SLDs (P) in a way that allows components that are already *active* to be used as much as possible, so other components may be turned off. We define the following variables to be used in our ILP.

- $r^p_{i,m}$ = 1, if lightpath p uses IP router at node i during interval m.
- $s^p_{i,m}$ = 1, if lightpath p uses optical switch at node i during interval m.
- $r_{i,m}$ = 1, if IP router at node i is being used during interval m.
- $s_{i,m}$ = 1, if optical switch at node i is being used during interval m.
- $t^p_{e,m}$ = 1, if link e is being used by lightpath p during interval m.
- $t_{e,m}$ = 1, if link e is being used during interval m.
- $\omega_{k,p}$ = 1, if lightpath p uses channel k.
- $y_{p,i}$ = 1, if lightpath p uses node i.
- $x_{e,p}$ = 1, if lightpath p uses link e.
- $d_{p,i}$ = 1, if node i is selected as destination node for lightpath p.
- $a_{p,m}$ = 1, if lightpath p is active during interval m.
- $st_{p,m}$ = 1, if m is the starting interval for lightpath p.
- $a^p_{k,e}$ = 1, if lightpath p uses channel k on link e.

$$Min \sum_m [\sum_{i \in N}(C^s_{ip} \cdot r_{i,m} + \sum_{p \in P} C^d_{ip} \cdot r^p_{i,m}) + \sum_{i \in N}(C^s_{sw} \cdot s_{i,m} + \sum_{p \in P} C^d_{sw} \cdot s^p_{i,m}) + \sum_{e \in E} C^e_{link} \cdot t_{e,m}] \tag{4}$$

subject to:

a) Destination node selection constraints:

$$\sum_{i \in D_p} d_{p,i} = 1; d_{p,i} = 0, \forall i \notin D_p, \forall p \in P \tag{5}$$

b) Route selection constraints:

$$\sum_{e:(i,j) \in E} x_{e,p} - \sum_{e:(j,i) \in E} x_{e,p} = \begin{cases} 1 & \text{if } i = s_p, \\ -d_{p,i} & \text{otherwise.} \end{cases} \quad \forall i \in N, p \in P \tag{6}$$

c) IP router usage constraints:

$$d_{p,i} + a_{p,m} - r^p_{i,m} \le 1 \quad \forall p \in P, i \in D_p, \alpha_p \le m \le \omega_p \tag{7a}$$

$$d_{p,i} \ge r^p_{i,m}; a_{p,m} \ge r^p_{i,m} \quad \forall p \in P, i \in D_p, \alpha_p \le m \le \omega_p \tag{7b}$$

$$\frac{\sum_p r_{i,m}^p}{M} \leq r_{i,m} \quad \forall i \in D_p, \alpha_p \leq m \leq \omega_p \tag{7c}$$

$$r_{i,m} \leq \sum_p r_{i,m}^p \quad \forall i \in D_p, \alpha_p \leq m \leq \omega_p \tag{7d}$$

d) Optical switch usage constraints:

$$a_{p,m} + (y_{p,i} + d_{p,i}) - s_{i,m}^p \leq 1 \quad \forall p \in P, i \in D_p, \alpha_p \leq m \leq \omega_p \tag{8a}$$

$$a_{p,m} \geq s_{i,m}^p; (d_{p,i} + y_{p,i}) \geq s_{i,m}^p \quad \forall p \in P, i \in D_p, \alpha_p \leq m \leq \omega_p \tag{8b}$$

$$\frac{\sum_p s_{i,m}^p}{M} \leq s_{i,m} \quad \forall i \in D_p, \alpha_p \leq m \leq \omega_p \tag{8c}$$

$$s_{i,m} \leq \sum_p s_{i,m}^p \quad \forall i \in D_p, \alpha_p \leq m \leq \omega_p \tag{8d}$$

e) Fiber link and node usage constraints:

$$x_{e,p} + a_{p,m} - t_{e,m}^p \leq 1 \quad \forall p \in P, i \in D_p, \alpha_p \leq m \leq \omega_p \tag{9a}$$

$$a_{p,m} \geq t_{e,m}^p; x_{e,p} \geq t_{e,m}^p \quad \forall p \in P, i \in D_p, \alpha_p \leq m \leq \omega_p \tag{9b}$$

$$\frac{\sum_p t_{e,m}^p}{M} \leq t_{e,m} \quad \forall i \in D_p, \alpha_p \leq m \leq \omega_p \tag{9c}$$

$$t_{e,m} \leq \sum_p t_{e,m}^p \quad \forall i \in D_p, \alpha_p \leq m \leq \omega_p \tag{9d}$$

$$y_{p,i} = \sum_{j:(i \to j \in E)} x_{e,p} \quad \forall p \in P, i \in N \tag{9e}$$

f) RWA constraints:

$$\sum_{k \in K} \omega_{k,p} = 1, \quad \forall p \in P \tag{10}$$

$$\omega_{k,p} + x_{e,p} - a_{k,e}^p \leq 1; \quad \forall k \in K, e \in E, p \in P \tag{11a}$$

$$\omega_{k,p} \geq a_{k,e}^p; \quad \forall k \in K, e \in E, p \in P \tag{11b}$$

$$x_{e,p} \geq a_{k,e}^p; \quad \forall k \in K, e \in E, p \in P \tag{11c}$$

$$a_{k,e}^p + a_{p,m} + a_{k,e}^q + a_{q,m} \leq 3 \quad \forall k \in K, e \in E, p, q \in P, \alpha_p \leq m \leq \omega_p \tag{12}$$

g) Demand scheduling constraints:

$$\sum_m st_{p,m} = 1, \quad \forall p \in P, \alpha_p \leq m \leq \omega_p \tag{13}$$

$$\sum_m a_{p,m} = \tau_p, \quad \forall p \in P, \alpha_p \leq m \leq \omega_p \tag{14}$$

$$a_{p,m+j} \geq st_{p,m}, \quad \forall p \in P, 0 \leq j < \tau_p, \alpha_p \leq m \leq \omega_p \tag{15}$$

Equation (4) is the objective function, which minimizes the overall energy consumption at IP routers, optical switches and fiber links. Constraint (5) selects exactly one destination for each SLD $p \in P$, and also ensures that only nodes belonging D_p can be selected as destination nodes. Constraint (6) is the standard flow conservation constraint and is used to find a feasible path from the source to the selected destination. Constraints (7a) - (7d) together determine if IP router at node i is being used during interval m. Similarly, Constraints (8a) - (8d) determine if optical switch at node i is being used during interval m. Constraints (9a) - (9d) state that fiber link e is in use during time interval m, if there is at least one SLD $p \in P$ such that p uses link e and is active during interval m. Constraint (9e) states that node $i \in N$ is used by demand p, if p uses edge $e : i \rightarrow j$.

Constraint (10) enforces the wavelength continuity constraint, so that each demand p is allocated the same channel on each fiber it traverses. Constraints (11a) - (11c) set the value of $a^p_{k,e} = 1$, if lightpath p uses channel k on link e. Constraint (12) enforces the wavelength clash constraint and ensures that two lightpaths p and q cannot use the same channel k on the same link e if they are both active during the same interval m. Finally constraints (13)-(15) are used to select the best starting interval for each SLD. Constraint (13) ensures that exactly one interval is selected as the starting interval for demand p. Constraint (14) states that the number of active intervals for demand p must equal its demand holding time τ_p. Finally, constraint (15) ensures that all the active intervals for demand p are assigned consecutively, with no gaps in between.

3.1. An Illustrative Example

In order to illustrate the effectiveness of the proposed approach, we consider a very simple example where three demands are to be scheduled and routed over the topology in Fig. 1(a). The demands $p1$, $p2$ and $p3$ are specified as shown below:

- $p1 = (2, \{1\}, 2, 4, 2)$: The source node $s1 = 2$; the set of potential destinations $D1 = \{1\}$; the demand must be scheduled between intervals $\alpha 1 = 2$, $\omega 1 = 4$ and the demand holding time $\tau 1 = 2$ intervals.
- $p2 = (1, \{3\}, 1, 4, 3)$: The source node $s2 = 1$; the set of potential destinations $D2 = \{3\}$; the demand must be scheduled between intervals $\alpha 2 = 1$, $\omega 2 = 4$ and the demand holding time $\tau 2 = 3$ intervals.
- $p3 = (2, \{3, 4\}, 3, 5, 2)$: The source node $s2 = 2$; the set of potential destinations $D3 = \{3, 4\}$; the demand must be scheduled between intervals $\alpha 3 = 3$, $\omega 3 = 5$ and the demand holding time $\tau 3 = 2$ intervals.

In order to simplify the explanation, we assume that demands $p1$ and $p2$ have already been routed along the routes $2 \rightarrow 1$ and $1 \rightarrow 3$ respectively, using channel $\lambda 1$, as shown in Fig. 1a. Furthermore, we assume that demands $p1$ and $p2$ have been scheduled to start at time interval $m = 3$ and $m = 2$ respectively, as shown in Fig. 1b.

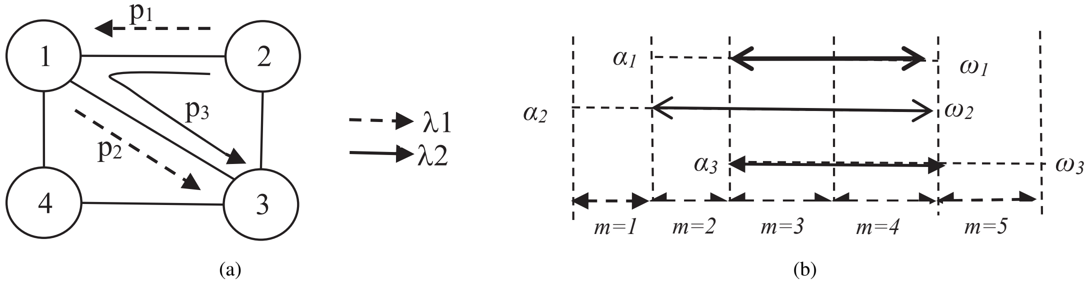


Fig. 1. (a) Routing and (b) scheduling of three demands over a 4-node physical topology.

Under this scenario, there are a number of options for routing and scheduling demand $p3$. Six valid options for demand $p3$ are given below. We note that this is not an exhaustive list, and there are other options that can be used. We are simply listing the following options to illustrate that there are many different ways a single demand may be accommodated.

- *Option 1*: Select node 3 as the destination, use route $2 \rightarrow 3$ and schedule the demand to start in interval $m = 3$.
- *Option 2*: Select node 3 as the destination, use route $2 \rightarrow 1 \rightarrow 3$ and schedule the demand to start in interval $m = 3$.
- *Option 3*: Select node 3 as the destination, use route $2 \rightarrow 3$ and schedule the demand to start in interval $m = 4$
- *Option 4*: Select node 4 as the destination, use route $2 \rightarrow 1 \rightarrow 4$ and schedule the demand to start in interval $m = 3$
- *Option 5*: Select node 4 as the destination, use route $2 \rightarrow 1 \rightarrow 4$ and schedule the demand to start in interval $m = 4$
- *Option 6*: Select node 4 as the destination, use route $2 \rightarrow 3 \rightarrow 4$ and schedule the demand to start in interval $m = 4$

Assuming demands $p1$ and $p2$ have been allocated as mentioned above, we see that Option 2 allows the maximum sharing of resources and consequently reduces energy consumption. For example, since node 3 is selected as destination node for $p3$, this allows node 4 to remain in a low-power (inactive) state. Also, route $2 \rightarrow 1 \rightarrow 3$ is selected, rather than the shorter route $2 \rightarrow 3$, because both links $2 \rightarrow 1$ and $1 \rightarrow 3$ are already in use by other demands. This means the optical amplifiers on link $2 \rightarrow 3$ can remain in low-power state. Finally, scheduling $p1(p2)$ to start during interval $m = 3(m = 2)$ rather than the earliest possible times for those demands, allows $p1$ and $p2$ to remain active for the entire duration of $p3$, so that network components are active for a minimum amount of time.

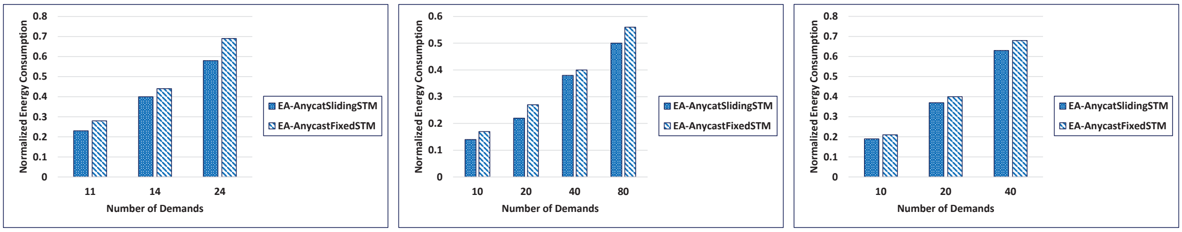
4. Simulation Results

In this Section, we present simulation results, obtained using our proposed ILP formulations. We considered three well known topologies ranging in size from 11 nodes to 24 nodes. This includes the standard NSFNET[22], COST-239[21], and USA network[23]. The ILP is able to generate optimal results for practical sized problems. The simulations were carried out with IBM ILOG CPLEX 12.6.2[24]. We have performed experiments considering 10, 20, 40 and 80 lightpaths. The results reported below correspond to average values (rounded to the nearest integer) over 5 different runs. For each given network topology, we have tested our proposed approach with different sized demand sets and different demand time correlations δ as defined in[19]. The demand time correlation δ determines the overlapping between different demands. If $\delta = 0$, it means that the demands do not overlap in time, so RWA can be done for each demand separately. For the simulations we have considered two distinct scenarios:

- Energy aware anycast sliding scheduled traffic model (EA-AnycastSlidingSTM): This is our proposed approach, where the ILP selects the best possible destination node and start time for each demand, and then performs RWA.
- Energy aware anycast fixed window traffic model (EA-AnycastFixedSTM): In this case the ILP is free to choose a suitable destination node, but the start time of each demand is fixed.

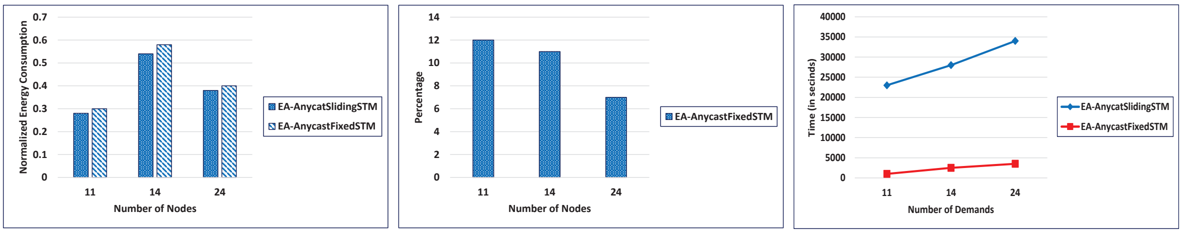
It has already been shown that energy-aware anycast routing under the fixed window STM (EA-AnycastFixedSTM), where demand start and end times are specified beforehand, can lead to energy savings compared to both energy-unaware anycast and energy-aware unicast approaches[12]. In this section, we investigate how much additional improvements can be achieved, even over the previous best performing model (EA-AnycastFixedSTM), by allowing flexible scheduling of the SLDs in time, using our proposed model (EA-AnycastSlidingSTM). Fig. 2a shows the normalized energy consumption for routing a set of SLDs over the 11-node (COST239) topology for 16 channels per fiber. It is clearly seen that the proposed approach (EA-AnycastSlidingSTM) performs better than EA-AnycastFixedSTM irrespective of the number of demands. EA-AnycastSlidingSTM shows improvement about 13%, 11%, and 7% over EA-AnycastFixedSTM for 10, 20, 40 lightpath demands respectively. As expected, the overall trend shows an increase in energy consumption with increase in number of demands, since more network components such as switches, routers and amplifiers will be required to turn on. In Fig. 2b and 2c the comparison of energy consumption for

14-node topology with 21 links (NSFNET) and 24-node with 43 links is illustrated. For 14-node topology, we have performed experiments with 10, 20, 40 and 80 lightpath demands. For 24 node topology, the experiments were performed on 10, 20 and 40 lightpath demands. For both networks, the proposed sliding scheduled traffic demands allocation model outperforms the fixed approach(EA-AnycastFixedSTM). The energy consumption also increases as the number of demands increase for both the topologies. The average improvement over the next best approach (EA-AnycastFixedSTM) is 13%, 11% and 7% for with 10, 20 and 40 demands respectively. We next consider results for different networks with the same number of demands as illustrated in Fig. 3a. We can see that the energy consumption is more in the case of 14-node topology compared to 11-node topology for all the approaches, but the energy consumption for 24-node topology is less compared to 14-node topology although 24-node topology includes more nodes and links compared to 14-node topology. This can be due to a number of factors, such as the length of the links, the number of available destination nodes, and the distribution of the demands. In Fig. 3b we show the relative improvement obtained using our proposed scheme over EA-AnycastFixedSTM scheme. EA-AnycastSlidingSTM shows 12% improvement on 11-node topology, 11% improvement on 14-node topology and 7% improvement on 24-node topology comparing to next best technique EA-AnycastFixedSTM. We next consider the comparison of execution times of our proposed approach with the other approaches. The simulation results show that fixed window traffic allocation requires significantly less time compared to sliding scheduled demand allocation. The reason is that the additional flexibility in demand start time leads to an increase in the number of integer variables, which results in a much larger search space. Fig. 3c shows that the execution time increases with number of nodes, increases as expected. The EA-AnycastSlidingSTM shows linear steady growth in execution time with increase in number of nodes and consumes large time compared to EA-AnycastFixedSTM as expected.



(a) (b) (c)

Fig. 2. Comparison of energy consumption for sliding and fixed schedule traffic with different demand set sizes (a) 11-node network (COST239), (b) 14-node network (NSFNET), and (c) 24-node network.



(a) (b) (c)

Fig. 3. (a) Comparison of energy consumption for sliding and fixed schedule traffic for different network topologies, (b) Improvement of EA-AnycastSildingSTM over EA-AnycastFixedSTM and (c) Comparison of execution time for EA-AnycastSildingSTM and EA-AnycastFixedSTM.

5. Conclusion

In this paper, we have presented a new approach for energy-aware RWA, which jointly schedules demands (in time) and exploits the flexibility of anycast routing to minimize the overall energy consumption of the network. Our approach implements a comprehensive energy-aware resource allocation for optical grid networks, which is able to consider power consumption over a wide variety of network components. To the best of our knowledge, this is the first optimal ILP formulation for sliding scheduled lightpath demands with the objective of energy minimization for optical grid networks. We have compared our results with previous best technique, using fixed window demand allocation model. The results demonstrate that the proposed approach can significantly lower energy consumption, even compared to previous energy-aware routing for lightpaths with pre-specified start and end times.

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