# Optimal Energy Price-Aware Resource Allocation Scheme for Scheduled Lightpath Demands

Karan Neginhal, Saja Al Mamoori, Arunita Jaekel
School of Computer Science
University of Windsor
Windsor, Canada
Email: {neginha, sajak, arunita}@uwindsor.ca

*Abstract*—**Electricity costs comprise a significant portion of operating expenses forData Center Networks (DCNs). As a result, energy-aware Routing and Wavelength Assignment schemes (RWA), which try to minimize the overall energy consumption for data transmission, have received considerable attention in the past decade. Recently, the idea of minimizing the dollar cost of energy consumption using Real-Time Pricing (RTP) has been proposed for Wavelength-Division Multiplexing (WDM) optical networks. The RTP-based RWA has been shown to result in reduced electricity costs. In this paper, we present a new formulation for optimal RWA for scheduled lightpath demands using the RTP model. Our results indicate that the proposed approach clearly outperforms the Flat-Rate Price (FRP) model, as well as traditional shortest path routing schemes.**

***Keywords–Data Center Networks (DCNs); Energy-aware resource allocation; Routing and Wavelength Assignment (RWA); Real-Time Price (RTP).***

## I. Introduction

Data Center Networks (DCNs) are one of the fastest growing consumers of electricity due to the rapid increase of digital content, big data, e-commerce and Internet traffic [1]-[5]. The electricity costs comprise a significant portion of operating expenses for such networks [6]-[10]. To mitigate this problem, the development of energy efficient schemes is crucial at all levels of network infrastructure, including data transmission. Many Routing and Wavelength Assignment (RWA) schemes that minimize energy consumption at network nodes and/or fiber links have been proposed in the literature for data transfer over an optical network [11]-[13]. However, energy prices using the RTP model can vary widely, depending on geographic location. Therefore, minimizing energy consumption may not necessarily result in the least dollar cost. Wavelength-Division Multiplexing (WDM) in optical networks is the technology that allows multiplexing a number of optical carrier signals onto a single optical fiber by using different wavelengths. In this study, we propose an energy-aware RWA optimal algorithm, which aims to minimize the dollar cost in WDM optical networks using RTP the model.

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 reducing Electrical-Optical-Electrical (E-O-E) conversions [14], switching off or slowing down unused network elements [15][16] putting selected network components in sleep mode [17], and using intelligent traffic grooming techniques [18][19]. Energy aware unicast routing in WDM networks has received considerable research attention in the last ten years [20].

In many applications, the physical location of the server or other network resources remains hidden from the user as it is not important. In this scenario, it is possible to select the best destination from the set of possible destinations to execute a job. This is known as *anycast routing* [21]. 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. Both heuristics and optimal formulations energy-aware approaches using anycast routing have been considered in [22]-[24]. The goal is to reduce both the static and the dynamic (load dependent) portions of power consumption as much as possible, although static power consumption typically dominates for most network components [24].

In WDM optical networks, there are mainly three different demand allocation models:

1) **Static traffic model**: Where the set of demands is fixed and known in advance.
2) **Dynamic traffic model**: Where the start time and the end time of the demands are known in advance. The set of demands is generated based on certain distributions.
3) **Scheduled traffic model**: Where the set of demands is predictable and periodic in nature.

In Scheduled Traffic Demands (STDs), the setup time and the tear down time for the demand is known in advance. The Scheduled Traffic Model (STM) is further divided into two different models, known as *fixed window traffic* model and *sliding scheduled traffic* model. A number of recent papers have shown how *anycast* routing can be used for minimizing the overall energy consumption in optical networks [23]-[25]. However, these papers mostly deal with the static [26][27] or dynamic [12][13] traffic models. In our previous work, we have considered energy-aware routing and traffic grooming of sub-wavelength demands, under STM [28]. Although energy aware routing for WDM networks has received significant attention in recent years, the idea of utilizing the anycast concept for energy minimization [16][23][25] has been less well studied.

Replication in DCNs makes it possible to have multiple copies of data on different Data Centers (DCs) [29]. Adding more replicas improves reliability, lowers latency across the network, and allows more flexibility in choosing energy efficient routes; but it also increases the costs for network equipment and storage [30]. Very recently, researchers have proposed reducing the operational expenditures by choosing the route with the least cost for the energy consumed based on Real-Time Pricing (RTP) [31]. They considered price changes throughout the day and for different US time zones. The Least Dollar Path (LDP) approach in [31] considers the real-time energy costs and replicated data storage to avoid costly peak charges and reduce the overall energy cost. The flat rate pricing model leads to more electricity costs as compared to the real-time pricing model [31]. Efficient routing schemes and proper arrangement of the replicas can lower energy consumption in the DCNs [31].

In this paper, we present a new Integer Linear Program (ILP) formulation for RTP-based optimal RWA of scheduled lightpath demands. Under STM, the setup and teardown times of the demands are known in advance, so that the RWA algorithm can optimize resource allocation in both space and time [32]. The proposed ILP not only selects the appropriate data center node to serve each request, but also performs RWA that leads to the least dollar cost. A heuristic algorithm for solving this problem has been presented in [33]. To the best of our knowledge, RTP-based energy-aware RWA for advance reservation under the fixed-window STM has not been considered before. Our approach differs from the previous RTP-based RWA as follows:

- We consider energy consumption not only at network nodes, but along fiber links as well.
- We process the set of demands as a whole, rather than adopt a greedy approach where each demand is processed one at a time.
- We consider both static and dynamic components of power consumption of nodes and links.

The remainder of the paper is organized as follows. In Section II, we outline our network energy model and propose an optimal formulation for energy-aware routing. In Section III, we present and analyze our simulation results and discuss our conclusions with some directions for future work in Section IV.

## II. Energy Efficient Anycast Routing For Fixed Window Scheduled Traffic Model

In this section, we introduce the proposed optimal algorithm formulated as an ILP using the anycast principle for fixed window scheduled lightpath demands allocation. The objective here is to minimize the overall electricity costs of a DCN by reducing the actual energy consumption.

### A. Network Energy Model

We consider a transparent IP-over-WDM network, which consists of optical cross connect switches (OXCs) connected to an IP router [34]. We consider power consumption both at network nodes and fiber links [24]. The total power consumption of the IP router and optical switch can be calculated using the following equations.

$$P_{IP} = P^s_{IP} + \pi_{IP} * t_{IP} \tag{1}$$

$$P_{SW} = P^s_{OXC} + \pi_{OXC} * t_\lambda \tag{2}$$

In (1) and (2), $P^s_{IP}$ and $P^s_{OXC}$ denote the static power consumption for the IP router and the optical switch, respectively. Similarly, $\pi_{IP}$ and $\pi_{OXC}$ denote the dynamic, i.e. traffic dependent, power consumption for the IP router and the optical switch, respectively. The terms $t_{IP}$ and $t_\lambda$ indicate the amount of traffic flowing through the IP router and the switch, respectively.

TABLE I. POWER CONSUMPTION OF NETWORK DEVICES [35][36].

| Device | Symbol | Power Consumption |
|---|---|---|
| IP router (static) | $P^s_{IP}$ | 150 W |
| OXC (static) | $P^s_{OXC}$ | 100 W |
| IP router (dynamic) | $\pi_{IP}$ | 17.6 W |
| OXC (dynamic) | $\pi_{OXC}$ | 1.5 W |
| Transponder (dynamic) | $\pi_{XT}$ | 34.5 W |
| Pre-amplifier | $P_{pre}$ | 10 W |
| Post-amplifier | $P_{post}$ | 20 W |
| Inline-amplifier | $P_{inline}$ | 15 W |

The power consumption of a link is obtained using (3), where $P_{pre}$, $P_{post}$ and $P_{inline}$ are the power consumed by pre, post, and inline amplifiers, respectively. The actual values of these parameters, used in our simulations, are taken from [35] and [36] and shown in TABLE I.

$$P_e = P_{pre} + P_{post} + P_{inline} \tag{3}$$

### B. Solution Approach

We consider a set of fixed window lightpath demands and propose a *minimum cost path* using RTP (MCP-RTP) model to select the route and destination for each demand in such a way that the overall electricity costs are minimized. The notation used in our ILP is given below.

### C. Notation used in this paper

$\boldsymbol{G(N,E)}$: Physical topology, where $N$ is set of nodes and $E$ is the set of bidirectional edges (i.e., links) in the network.
$\boldsymbol{N}$: Set of data center nodes.
$\boldsymbol{(i,j)}$: An edge in the network from node $i$ to node $j$.
$\boldsymbol{Q}$: Set of lightpath demands to be routed over the physical topology. Each demand is a tuple $(s_q, st_q, \tau_q)$, where $s_q$ is the source node for demand $q$, $st_q$ is the starting time for demand $q$ and $\tau_q$ denotes the holding time for demand $q$.
$\boldsymbol{m}$: $= 0, 1, 2, ...m_{max}$, where $m$ is the number of intervals ($0 \leq m \leq 23$).
$\boldsymbol{a_{q,m}}$: = 1 if demand $q$ is active during interval $m$.
$\boldsymbol{l_e}$: length of edge $e$.

*Binary Variables*
$\boldsymbol{IP_{i,m}}$: = 1, if the IP router at node $i$ is active at interval $m$.
$\boldsymbol{OXC_{i,m}}$: = 1, if OXC at node $i$ is active at interval $m$.
$\boldsymbol{L_{e,m}}$: = 1, if link $e$ is in use at interval $m$.
$\boldsymbol{x_{q,e}}$: = 1, if lightpath $q$ uses link $e$.
$\boldsymbol{y_{q,i}}$: = 1, if lightpath $q$ uses node $i$.
$\boldsymbol{dc_{q,i}}$: = 1, if DC node $i$ is selected as a destination for lightpath $q$.

*Bounded Variables*
$\boldsymbol{\beta^q_{i,m}}$: = 1, if lightpath $q$ uses IP router at node $i$ during interval $m$.
$\boldsymbol{\gamma^q_{i,m}}$: = 1, if lightpath $q$ uses OXC at node $i$ during interval $m$.

$\boldsymbol{\sigma^q_{e,m}}$: = 1, if lightpath $q$ uses link $e$ during interval $m$.

$$minimize \sum_m \left[ \sum_i cost_{i,m} \left[ P^s_{IP} \dot{+} \pi_{IP} \sum_q \beta^q_{i,m} + \left( P^s_{i,m} \dot{O}XC_{i,m} \pi_{OXC} \sum_q \gamma^q_{i,m} \right) + \left( \pi_{XT} \sum_q \beta^q_{i,m} \right) \right] + cost_{j,m} \sum_{e:(i,j)} P_e \dot{L}_{e,m} \right]$$

$$\sum_{e:(i,j)\in E} x_{q,e} - \sum_{e:(j,i)\in E} x_{q,e} = \begin{cases} dc_{q,i}, \text{if } i = source, \\ -dc_{q,i}, \text{if } i = destination, \\ 0, \text{otherwise.} \end{cases} \tag{4}$$

Constraint (4) must be satisfied $\forall i \in N, q \in Q$

$$y_{q,i} = \sum_{e:(i,j)\in E} x_{q,e} \quad \forall i \in N, q \in Q \tag{5}$$

$$\sum_q x_{q,e} \cdot a_{q,m} \leq |K| \quad \forall e \in E, 1 \leq m \leq m_{max} \tag{6}$$

$$\sum_{i\in S} dc_{q,i} = 1 \quad \forall q \in Q; \quad dc_{q,i} = 0 \quad \forall i \notin S, q \in Q \tag{7}$$

IP router usage:

$$dc_{q,i} + a_{q,m} - \beta^q_{i,m} \leq 1 \tag{8}$$

$$dc_{q,i} \geq \beta^q_{i,m} \tag{9}$$

$$a_{q,m} \geq \beta^q_{i,m} \tag{10}$$

$$IP_{i,m} \geq \beta^q_{i,m} \tag{11}$$

$$IP_{i,m} \leq \sum_q \beta^q_{i,m} \tag{12}$$

Constraints (8) - (12) must be satisfied $\forall i \in S, q \in Q, 1 \leq m \leq m_{max}$.

OXC switch usage:

$$(dc_{q,i} + y_{q,i}) + a_{q,m} - \gamma^q_{i,m} \leq 1 \tag{13}$$

$$(dc_{q,i} + y_{q,i}) \geq \gamma^q_{i,m} \tag{14}$$

$$a_{q,m} \geq \gamma^q_{i,m} \tag{15}$$

$$OXC_{i,m} \geq \gamma^q_{i,m} \tag{16}$$

$$OXC_{i,m} \leq \sum_q \gamma^q_{i,m} \tag{17}$$

Constraints (13) - (17) must be satisfied $\forall i \in N, q \in Q, 1 \leq m \leq m_{max}$.

Link usage:

$$x_{q,e} + a_{q,m} - \sigma^q_{e,m} \leq 1 \tag{18}$$

$$x_{q,e} \geq \sigma^q_{e,m} \tag{19}$$

$$a_{q,m} \geq \sigma^q_{e,m} \tag{20}$$

$$L_{e,m} \geq \sigma^q_{e,m} \tag{21}$$

$$L_{e,m} \leq \sum_q \sigma^q_{e,m} \tag{22}$$

Constraints (18) - (22) must be satisfied $\forall e \in E, q \in Q, 1 \leq m \leq m_{max}$.

### D. Justification of the ILP

The objective function tries to minimize the dollar cost by using the real time electricity prices. The summation is over all intervals $m$ and for each network component, i.e., IP router, optical switch and fiber link. The term $cost_{i,m}$ is the real time electricity price at node $i$ during interval $m$. We have 24 intervals and for each interval the electricity price is different. For calculating the cost of a link $e : i \to j$, we have multiplied the energy consumption of the link $e$ with the RTP electricity cost at the destination node $j$ of that link.

Constraint (4) is the standard flow conservation constraint, which finds a feasible path from source node $s_q$ to the selected data center (destination) node $dc_{q,i}$ for each demand $q$. Constraint (5) ensures that if lightpath $q$ traverses link $e : i \to j$ the value of $y_{q,i}$ is set to 1. Constraint (6) ensures that the total number of demands traversing link $e : i \to j$ does not exceed the number of available channels $|K|$. Constraint (7) ensures that exactly one data center is selected as the destination node for lightpath $q$.

Constraints (8) - (12) are the *IP router usage* constraints. They are used to determine if a particular IP router at node $i$ is active during interval $m$. Constraints (8) - (10) are used to set the value of $\beta^q_{i,m}$. Constraint (8) sets $\beta^q_{i,m}$ to 1 if lightpath $q$ is active during interval $m$ and DC node $i$ is selected as a destination for lightpath $q$. Constraints (9) and (10) ensure that $\beta^q_{i,m}$ is set to 0 if either $dc_{q,i}$ or $a_{q,m}$ is 0. Constraint (11) ensures that if the IP router is active at node $i$ during interval $m$ it is used by at least one lighthpath $q$. Constraint (12) ensures that if there is no lightpath $q$ using the IP router at node $i$ during interval $m$ then the IP router is not active during that interval $m$, i.e., $IP_{i,m}$ = 0.

Constraints (13) - (17) are the *optical switch usage* constraints. They are used to determine if a particular optical

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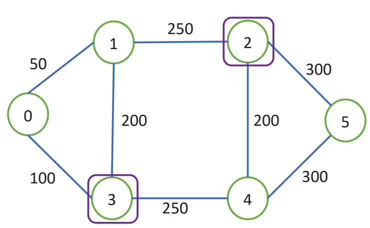
switch at node $i$ is active during interval $m$. Constraints (13) - (15) are used to set the value of $\gamma^q_{i,m}$. Constraint (13) sets $\gamma^q_{i,m}$ to 1 if lightpath $q$ is active during interval $m$ and uses the OXC at node $i$. Constraints (14) and (15) ensure that $\gamma^q_{i,m}$ is set to 0, if either $dc_{c,q} + y_{q,i}$ or $a_{q,m}$is 0 . Constraint (16) ensures that the OXC switch is active at node $i$ during interval $m$ if it is used by at least one lightpath $q$. Constraint (17) ensures that if there is no lightpath $q$ using OXC switch at node $i$ during interval $m$, then the OXC switch is not active during that interval $m$, i.e., $OXC_{i,m}$= 0.

Constraints (18) - (22) are the *link usage* constraints. They are used to determine if a particular link is active during interval $m$. Constraints (18) - (20) are used to set the value of $\sigma^q_{e,m}$. Constraint (18) sets $\sigma^q_{e,m}$ to 1 if lightpath $q$ uses link $e$ and is active during interval $m$. Constraints (19) and (20) ensure that $\sigma^q_{e,m}$ is set to 0 if either $x_{q,e}$ or $a_{q,m}$is 0 . Constraint (21) ensures that link $e$ is active during interval $m$ if it is used by at least one lightpath $q$. Constraint (22) ensures that if there is no lightpath $q$ using link $e$ during interval $m$, then the link is not active during that interval $m$, i.e., $L_{e,m}$ = 0.

### E. An Illustrative Example

To illustrate the effectiveness of the proposed approach, we consider a simple 6-node network with 8 bi-directional links. The physical topology used in this example is shown in Figure 1a. The label on each edge represents the length of the link in Km. Nodes 2 and 3 are identified as the data center nodes, which will serve as potential destinations for the connection (lightpath) demands.




(a)

| | $s_q$ | $st_q$ | $\tau_q$ |
|---|---|---|---|
| $LP_0$ | 1 | 5 | 8 |
| $LP_1$ | 4 | 4 | 15 |
| $LP_2$ | 5 | 0 | 7 |

(b)

Figure 1. (a) A sample physical topology and (b) A sample set of lightpath demands.

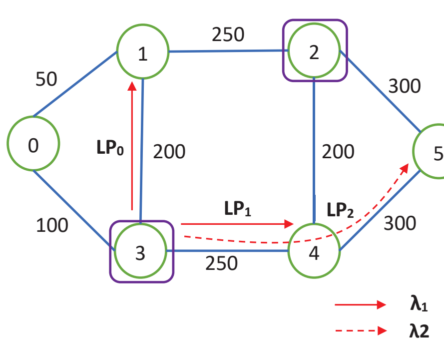



Figure 2. Routing of lightpath demands for the proposed objective.

A set of 3 lightpath demands is shown in Figure 1b, where $s_q$ indicates the source node, $st_q$ indicates the starting time interval for that demand and $\tau_q$ indicates the holding time for the demand, in terms of the number of time intervals. For example, according to the lightpath requests table, the lightpath LP0 originates from node 1, at interval 5 and is active for a total of 8 intervals. Based on our main objective, which tries to minimize the dollar costs by reducing the power consumption in the DCNs, the ILP selects the appropriate destination (i.e., data center node) and finds the "best" route with minimum dollar cost to the selected destination.

Figure 2 shows the routing scheme of lightpath demands on the given physical topology based on our objective, which minimizes the overall dollar cost. To explain how the lightpaths are routed based on our approach's minimum dollar cost objective, we consider the following examples:

- lightpath LP1 is using the route $3 \rightarrow 4$ where the selected data center is node 3. The approach could have chosen an alternative data center at node 2 if the objective was to minimize the distance, for instance.
- Similarly, lightpath LP2 is using the route $3 \rightarrow 4 \rightarrow 5$ with data center node 3 as the destination based on our objective. If the objective was to minimize the path distance or the number of hops, for example, then the ILP could have chosen the route $2 \rightarrow 5$ with data center node 2 as the destination instead.

## III. Simulation Results

For our simulations, we consider three well-known topologies: the 11-node COST-239, the 14-node NSFNET, and 24-node USANET [20]. The number of lightpath demands used in the simulations ranged from 40 to 120. The holding time of each demand ranged from 4 hours to 15 hours, with an average duration of 5 hours. The results reported in this section correspond to average values over 5 different runs. The simulation was carried out with IBM ILOG CPLEX 12.6.2.

Results are reported for four different approaches listed below, for different networks and traffic loads.

- The proposed ILP (*MCP-RTP*)
- The minimum hop path (*MHP*)
- The shortest distance path (*SDP*)
- The mininum cost path with flat rate pricing (*MCP-FRP*)

The dollar costs for routing 40 demands over different topologies and for three different approaches, our proposed approach, MCP-RTP, MHP, and SDP are shown in Figure 3. As seen in the figure, our main approach, which minimizes the electricity cost, has the lowest dollar cost for all cases, as expected. The improvement ranges from 36% - 62.9% compared to MHP approach which aims to minimize the path number of hops and 31.8% - 63.4% compared to SDP which minimizes the path distance.

A comparison of dollar costs for routing different demands over the 14-node topology, using the three approaches of Figure 3, is shown in Figure 4. A standard growth in the dollar cost values is observed with an increase in the demand size. As expected, our proposed approach MCP-RTP, performs better than the other approaches in reducing the dollar cost.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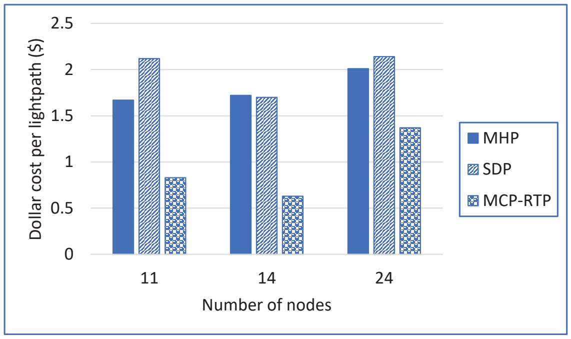


Figure 3. Comparison of electricity costs with different RWA approaches for different topologies and 40 demands

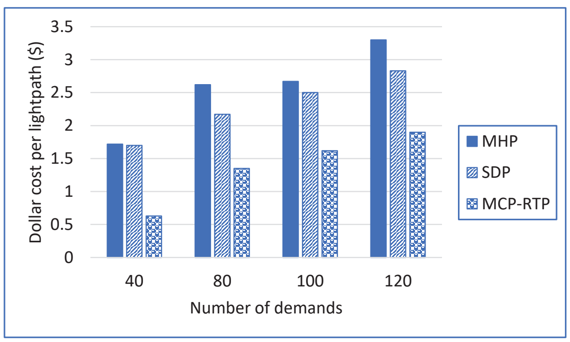


Figure 4. Comparison of electricity costs with different RWA approaches and different demands for NSFNET network

The improvement ranges from 32.9% - 63% over the MHP and 39.3% - 63.4% over SDP for all traffic loads.

In Figure 5, a comparison of the overall dollar cost is shown for routing 40 demands over the different topologies with our approach MCF-RTP and the MCF-FRP approach, which tries to minimize the dollar cost using the flat-rate price model. Our approach outperforms the MCF-FRP by reducing the electricity cost by an average of 60%.

We illustate how the overall cost varies with the number of demands for the 14-node NSFNET topology, for MCP-RTP and MCP-FRP routing schemes in Figure 6. As expected, the proposed method (MCP-RTP) clearly outperforms the others, with an average reduction of 53% in cost. We note that this reduction in cost comes at the expense of slightly longer paths for routing demands, in some cases.

## IV. Conclusion

In this paper, we have proposed an ILP for the RTP energy-aware RWA for the fixed window scheduled traffic model. We have considered the anycast routing scheme to select the best option for the destination node and the real-time pricing model for selecting lightpaths' routes. The objective of this model is to reduce the overall electricity cost by reducing the actual power consumption and using nodes and links with lower costs. Our simulation results indicate that the proposed

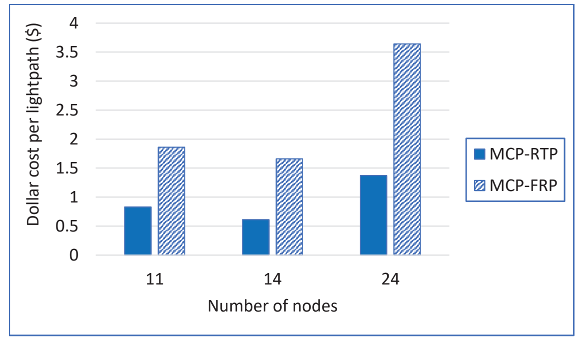


Figure 5. Comparison of electricity costs between MCF-RTP and MCF-FRP for different topologies and 40 demands

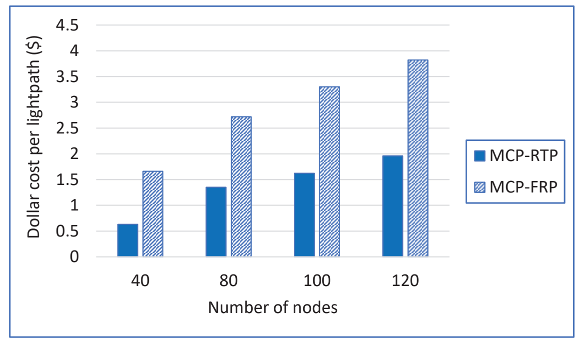


Figure 6. Comparison of electricity costs between MCF-RTP and MCF-FRP with different traffic loads for NSFNET

approach results in significant reductions in electricity costs, compared to both flat-rate pricing and traditional shortest-distance or minimum-hop routing.

In this work, we have primarily focused on energy costs. In the future, it will be interesting to incorporate other Quality of Service (QoS) metrics, such as bandwidth and delay into our model and evaluate the performance in terms of these metrics. It is also worthwhile to consider trade-offs of selecting the least cost path, which may have higher energy consumption, and compare the results with existing works that minimize energy consumption. Finally, this work can be extended to consider the sliding STM, so demand start times can be optimally adjusted, to further reduce energy costs.

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## References

[1] A. Deylamsalehi, Y. Cui, P. Afsharlar, and V. M. Vokkarane, "Minimizing electricity cost and emissions in optical data center networks," Journal of Optical Communications and Networking, vol. 9, no. 4, 2017, pp. 257–274.

[2] H.-P. Jiang, D. Chuck, and W.-M. Chen, "Energy-aware data center networks," Journal of Network and Computer Applications, vol. 68, 2016, pp. 80–89.

[3] Y. Lui, G. Shen, and W. Shao, "Energy-minimized design for ip over wdm networks under modular router line cards," in 2012 1st IEEE International Conference on Communications in China (ICCC), IEEE 2012, pp. 266–269.

[4] A. Qureshi, R. Weber, H. Balakrishnan, J. Guttag, and B. Maggs, "Cutting the electric bill for internet-scale systems," in ACM SIGCOMM computer communication review, vol. 39, no. 4, ACM, 2009, pp. 123–134.

[5] S. Yang, P. Wieder, R. Yahyapour, and X. Fu, "Energy-aware provisioning in optical cloud networks," Computer Networks, vol. 118, 2017, pp. 78–95.

[6] A. Ebrahimzadeh, A. G. Rahbar, and B. Alizadeh, "Pli-aware cost management for green backbone all-optical wdm networks via dynamic topology optimization," IEEE/OSA Journal of Optical Communications and Networking, vol. 10, no. 9, 2018, pp. 785–795.

[7] D. Rami, Energy Efficient Anycast Routing for Sliding Scheduled Lightpath Demands in Optical Grids. University of Windsor, 2016.

[8] S. Al Mamoori, D. Rami, and A. Jaekel, "Energy-efficient anycast scheduling and resource allocation in optical grids," Journal of Ambient Intelligence and Humanized Computing, vol. 9, no. 1, 2018, pp. 73–83.

[9] X. Dong, T. El-Gorashi, and J. M. Elmirghani, "Green ip over wdm networks with data centers," Journal of Lightwave Technology, vol. 29, no. 12, 2011, pp. 1861–1880.

[10] L. Rao, X. Liu, L. Xie, and W. Liu, "Minimizing electricity cost: optimization of distributed internet data centers in a multi-electricity-market environment," in INFOCOM, 2010 Proceedings IEEE. IEEE, 2010, pp. 1–9.

[11] K. Manousakis, A. Angeletou, and E. Varvarigos, "Energy efficient rwa strategies for wdm optical networks," IEEE/OSA Journal of Optical Communications and Networking, vol. 5, no. 4, 2013, pp. 338–348.

[12] S. Ricciardi, F. Palmieri, U. Fiore, D. Careglio, G. Santos-Boada, and J. Solé-Pareta, "An energy-aware dynamic rwa framework for next-generation wavelength-routed networks," Computer Networks, vol. 56, no. 10, 2012, pp. 2420–2442.

[13] A. Coiro, M. Listanti, and A. Valenti, "Dynamic power-aware routing and wavelength assignment for green wdm optical networks," in 2011 IEEE International Conference on Communications (ICC), IEEE, 2011, pp. 1–6.

[14] D. Tafani, B. Kantarci, H. T. Mouftah, C. McArdle, and L. P. Barry, "Distributed management of energy-efficient lightpaths for computational grids," in Global Communications Conference (GLOBECOM), 2012 IEEE. IEEE, 2012, pp. 2924–2929.

[15] A. Coiro, M. Listanti, A. Valenti, and F. Matera, "Energy-aware traffic engineering: A routing-based distributed solution for connection-oriented ip networks," Computer Networks, vol. 57, no. 9, 2013, pp. 2004–2020.

[16] C. Develder, M. Tornatore, M. F. Habib, and B. Jaumard, "Dimensioning resilient optical grid/cloud networks," in Communication Infrastructures for Cloud Computing. IGI Global, 2014, pp. 73–106.

[17] A. Coiro, M. Listanti, A. Valenti, and F. Matera, "Reducing power consumption in wavelength routed networks by selective switch off of optical links," IEEE Journal of Selected Topics in Quantum Electronics, vol. 17, no. 2, 2011, pp. 428–436.

[18] M. M. Hasan, F. Farahmand, and J. P. Jue, "Energy-awareness in dynamic traffic grooming," in Optical Fiber Communication (OFC), collocated National Fiber Optic Engineers Conference, 2010 Conference on (OFC/NFOEC). IEEE, 2010, pp. 1–3.

[19] S. Zhang, D. Shen, and C.-K. Chan, "Energy-efficient traffic grooming in wdm networks with scheduled time traffic," Journal of Lightwave Technology, vol. 29, no. 17, 2011, pp. 2577–2584.

[20] G. Shen and R. S. Tucker, "Energy-minimized design for ip over wdm networks," Journal of Optical Communications and Networking, vol. 1, no. 1, 2009, pp. 176–186.

[21] C. Develder, B. Dhoedt, B. Mukherjee, and P. Demeester, "On dimensioning optical grids and the impact of scheduling," Photonic Network Communications, vol. 17, no. 3, 2009, pp. 255–265.

[22] J. Buysse, C. Cavdar, M. De Leenheer, B. Dhoedt, and C. Develder, "Improving energy efficiency in optical cloud networks by exploiting anycast routing," in Communications and Photonics Conference and Exhibition, 2011. ACP. Asia. IEEE, 2011, pp. 1–6.

[23] Y. Chen and A. Jaekel, "Energy optimization in optical grids through anycasting," in Communications (ICC), 2013 IEEE International Conference on. IEEE, 2013, pp. 3835–3839.

[24] Y. Chen, A. Jaekel, and K. Li, "Energy efficient anycast routing for scheduled lightpath demands in optical grids," in Communications (QBSC), 2014 27th Biennial Symposium on. IEEE, 2014, pp. 10–13.

[25] B. G. Bathula and J. M. Elmirghani, "Energy efficient optical burst switched (obs) networks," in GLOBECOM Workshops, 2009 IEEE. IEEE, 2009, pp. 1–6.

[26] K. Zhu and B. Mukherjee, "Traffic grooming in an optical wdm mesh network," in Communications, 2001. ICC 2001. IEEE International Conference on, vol. 3. IEEE, 2001, pp. 721–725.

[27] K. Lee and M. A. Shayman, "Optical network design with optical constraints in ip/wdm networks," IEICE transactions on communications, vol. 88, no. 5, 2005, pp. 1898–1905.

[28] Y. Chen and A. Jaekel, "Energy aware resource allocation based on demand bandwidth and duration," Procedia Computer Science, vol. 10, 2012, pp. 998–1003.

[29] D. Abts, M. R. Marty, P. M. Wells, P. Klausler, and H. Liu, "Energy proportional datacenter networks," ACM SIGARCH Computer Architecture News, vol. 38, no. 3, 2010, pp. 338–347.

[30] A. Beloglazov, J. Abawajy, and R. Buyya, "Energy-aware resource allocation heuristics for efficient management of data centers for cloud computing," Future generation computer systems, vol. 28, no. 5, 2012, pp. 755–768.

[31] A. Deylamsalehi, P. Afsharlar, and V. M. Vokkarane, "Real-time energy price-aware anycast rwa in optical data center networks," in Computing, Networking and Communications (ICNC), 2016 International Conference on. IEEE, 2016, pp. 1–6.

[32] B. Wang, T. Li, X. Luo, Y. Fan, and C. Xin, "On service provisioning under a scheduled traffic model in reconfigurable wdm optical networks," in Broadband Networks, 2005. BroadNets 2005. 2nd International Conference on. IEEE, 2005, pp. 13–22.

[33] M. KHODA, Heuristic for Lowering Electricity Costs for Routing in Optical Data Center Networks. University of Windsor, 2018.

[34] K. Christodoulopoulos, K. Manousakis, and E. Varvarigos, "Offline routing and wavelength assignment in transparent wdm networks," IEEE/ACM Transactions on Networking (TON), vol. 18, no. 5, 2010, pp. 1557–1570.

[35] F. Musumeci, M. Tornatore, and A. Pattavina, "A power consumption analysis for ip-over-wdm core network architectures," Journal of Optical Communications and Networking, vol. 4, no. 2, 2012, pp. 108–117.

[36] A. Coiro, M. Listanti, A. Valenti, and F. Matera, "Power-aware routing and wavelength assignment in multi-fiber optical networks," Journal of Optical Communications and Networking, vol. 3, no. 11, 2011, pp. 816–829.