Power Consumption With Distance-Adaptive Load Balancing in Flexible Bandwidth Optical Networks

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Abstract—**In this paper, we propose a distance-adaptive load balancing algorithm to improve spectrum efficiency and to reduce power consumption in flexible bandwidth optical networks. Simulation results show that our proposed DALB algorithm significantly reduces blocking probability but consumes more power consumption compared to the traditional Dijkstra algorithm under the 40 Gbps, 100 Gbps, and mixed line rates, respectively. We should trade off between spectrum efficiency and power consumption when we consider distance-adaptive load balancing.**

Keywords- Flexible bandwidth optical networks; distance-adaptive load balancing; power consumption

I. INTRODUCTION

Currently, IP traffic from cloud computing and big data is emerging high-bandwidth applications. The spectrum efficiency and power consumption still need to be enhanced to satisfy the growing requirement. Thus, the great challenges to carry the IP traffic from the IP router ports to the optical layer are the spectrum efficiency and the power consumption. Considering the power consumption elements, the number of these elements should try to reduce them. Meanwhile, the optical regenerators must be placed on the intermediate node in order to satisfy the transmission quality of optical signal for each lightpath when connection requests are established. In previous papers, on one hand, energy and cost efficiency was investigated by considering the adaptive and mixed-line-rate (MLR) IP over DWDM networks [1]. On the other hand, different MLR network architectures were proposed to improve the energy efficiency in IP over optical networks [2]. In order to save power consumption, the number of the network power elements should try to reduce configuration, especially for the IP router ports, optical transponders, and optical regenerators. Thus, the previous papers [3-4] investigated the energy efficiency problems, and proposed different approaches to optimize the configuration of optical transponders and regenerators in flexible bandwidth optical networks. However, the load balancing problems are not investigated for both the spectrum efficiency and power consumption. Therefore, in this paper we focus on the effect of load balancing on the power consumption in flexible bandwidth optical networks.

II. NETWORK MODEL AND PROBLEM STATEMENT

A. Network Model

A flexible bandwidth optical network is defined as a network graph G($\boldsymbol{V}$, $\boldsymbol{E}$, $\boldsymbol{S}$), where $\boldsymbol{V}=\{v_1, v_2, v_3,\ldots,v_{|\boldsymbol{V}|}\}$ denotes a set of optical switching nodes, $\boldsymbol{E}=\{e_1, e_2, e_3,\ldots,e_{|\boldsymbol{E}|}\}$ denotes a set of fiber links, and $\boldsymbol{S}=\{s_1, s_2, s_3,\ldots, s_{|\boldsymbol{S}|}\}$ is a set of available frequency slots. $|\boldsymbol{V}|$, $|\boldsymbol{E}|$, and $|\boldsymbol{S}|$ represent the numbers of optical switching nodes, the number of fiber links, and the number of frequency slots in a fiber link, respectively. Each IP core router that includes a set of IP router ports is placed at each optical switching node. Each node $v_i \in \boldsymbol{V}$ corresponds to an optical switch node that contains a set of optical transponders and optical regenerators. A connection request consists of a source node s, a destination node d, and a bandwidth requirement (BR), which is described as:

$$\mathrm{CR}=\mathrm{CR}(s, d, BR) \tag{1}$$

The network power consumption consists of three parts: IP router ports, optical transponders, and optical regenerators. In order to reduce the power consumption for a given set of connection requests, the bandwidth requirement BR of a CR(s, d, BR) in G($\boldsymbol{V}$, $\boldsymbol{E}$, $\boldsymbol{S}$) should be carried by proper line rates, $\boldsymbol{R} = \{r_1, r_2, \cdots, r_{|\boldsymbol{R}|}\}$, modulation formats, $\boldsymbol{F} = \{f_1, f_2, \cdots, f_{|\boldsymbol{F}|}\}$, and reachability, $\boldsymbol{B} = \{b_1, b_2, \cdots, b_{|\boldsymbol{B}|}\}$, where $|\boldsymbol{R}|$ denotes total number of line rates, $|\boldsymbol{F}|$ denotes total number of modulation formats, $|\boldsymbol{B}|$ denotes total number of maximum reachability. In order to calculate the network power consumption, we should give a set of unit power of IP router ports, $\boldsymbol{\theta} = \{\theta_1, \theta_2, \cdots, \theta_{|\boldsymbol{\theta}|}\}$, a set of unit power of transponders corresponding to different line rates, $\boldsymbol{\varphi} = \{\varphi_1, \varphi_2, \cdots, \varphi_{|\boldsymbol{\varphi}|}\}$, where $|\boldsymbol{\varphi}|$ denotes total number of unit power of transponders, and a set of unit power of regenerators corresponding to different line rates, $\boldsymbol{\rho} = \{\rho_1, \rho_2, \cdots, \rho_{|\boldsymbol{\rho}|}\}$, where $|\boldsymbol{\rho}|$ denotes total number of unit power of regenerators. The power consumption of a connection request is calculated as follows:

$$PC = \sum_{r=r_1}^{r=r_{|\boldsymbol{R}|}} \alpha_r \times \theta_r + \sum_{r=r_1}^{r=r_{|\boldsymbol{R}|}} \beta_r \times \varphi_r + \sum_{r=r_1}^{r=r_{|\boldsymbol{R}|}} \gamma_r \times \rho_r \tag{2}$$

where α_r, β_r, and γ_r denote the number of IP router ports, the number of optical transponders, and the number of optical regenerators, respectively.

B. Problem Statement

For each connection request, CR(s, d, BR), we need to find a working path to carry the bandwidth requirement, BR, in flexible bandwidth optical networks. On a working path, a set of appropriate line rates and modulation formats that carry the bandwidth requirement of a connection request is determined to reduce the network power consumption. Different line rates and modulation formats have different reachability and we have to choose the proper line rate and modulation formats carefully to ensure signal quality along a path and to minimize the power consumption. In this paper, we consider 40 Gbps and 100 Gbps line rates and two modulation formats, DP-QPSK and DP-BPSK. Table 1 shows the unit power of optical transponders and optical regenerator for the two line rates, 40 Gbps and 100 Gbps, with different spectrum width, modulation formats, and reachability [4].

In order to avoid heavy load on some fiber link, we should consider the load balancing to reduce the blocking probability of connection requests by adaptively enlarging the distance of fiber links when the traffic load higher than the threshold, which is called distance-adaptive load balancing (DALB). We can use the following equation to describe DALB and use it to update the distance of each fiber link after a connection request is established in flexible bandwidth optical networks.

$$AL_{v_i,v_j} = \begin{cases} L_{v_i,v_j}, & 0 \le OS_{v_i,v_j} < \frac{2}{3}|\boldsymbol{F}| \\ 10 \times L_{v_i,v_j}, & \frac{2}{3}|\boldsymbol{F}| \le OS_{v_i,v_j} \le |\boldsymbol{F}| \end{cases} \tag{3}$$

where AL_{v_i,v_j} , L_{v_i,v_j} , and OS_{v_i,v_j} denote a DALB-based distance, a distance of a fiber link, and the occupied spectrum slots on a fiber link (v_i, v_j), respectively.

In order to investigate the spectrum efficiency and power consumption, we consider the single line rate, such as 40 Gbps with DP-QPSK and 100 Gbps with DP-BPSK and mixed line rates to carry the bandwidth requirements of a connection request in flexible bandwidth optical networks. Meanwhile, we should properly configure the optical transponders and optical regenerators when a lightpath is established to carry the bandwidth requirements. The objective is to improve the spectrum efficiency and reduce both blocking probability of connection requests and power consumption. On one hand, two optical transponders should be configured at the source node *s* and the destination node *d* for a CR(*s*, *d*, *BR*) due to the IP traffic downloading or uploading optical transponders. On the other hand, we should try to find the minimum number of placed regenerators on the working path for all connection requests under different line rates and modulation formats. For example, given an existing graph of a path, 1-2-3-4-5, in Fig. 1 (a), the total distance of this path is 2700 km from node 1 to node 5. Suppose a connection request, CR(1, 5, *BR*), from node 1 to node 5 is carried by using a 40 Gbps line rate for the modulation format DP-QPSK with a maximum reachability of 1800 km. The optical signal is not reachable for this CR(1, 5, *BR*), and several optical regenerators should be placed on the intermediate node, since 2700-km transmission distance is larger than its maximum reachability with 1800 km. In Fig. 1 (b), we can introduce an auxiliary graph to obtain the minimum number of optical regenerators that are placed to compensate for optical impairments. All the distances are calculated from the source node 1 to one of the destination nodes (2, 3, 4, and 5). Some of the node-pairs are connected with dashed line when the distance of this node-pair is less than the maximum reachability 1800 km, such as node-pair 1 and 3. Similarly, other node-pairs in the graph are evaluated for reachability. Next, the auxiliary graph is constructed, and the weight of each link in this auxiliary graph is assigned 1. The minimum hop count path from source node 1 to destination node 5 in the auxiliary graph is obtained by Dijkstra algorithm, and one regenerator is placed at node 3. Therefore, the number of regenerators required along a working path is equal to *h*-1, where *h* denotes the hop count from source node to destination node in the auxiliary graph.

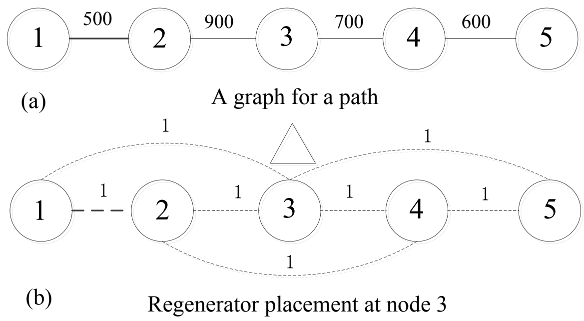

Fig. 2. Example of the regenerator placement at one line rate.

TABLE I. NETWORK PROFILES

Line rate (Gbps)	Parameters				
	Channel width(GHz)	*Modulation Format*	*Reachability (Km)*	*Transponder (W)*	*Regenerator(W)*
40	25.0	DP-QPSK	1800	159	225
100	37.5	DP-BPSK	1700	260	450

III. DISTANCE-ADAPTIVE LOAD BALANCING ALGORITHM

In order to improve the spectrum efficiency, we first propose a DALB algorithm to reduce the blocking probability and power consumption in flexible bandwidth optical networks. We also introduce the traditional Dijkstra algorithm to compare with a DALB algorithm. These two algorithms are described as follows.

A. DALB Algorithm

Step 1: For each CR(*s*, *d*, *BR*), we run the K shortest path (K-SP) algorithm to find *K* working paths from source node *s* to destination node *d*. If no working path can be found, block this CR(*s*, *d*, *BR*), else run **Step 2**;

Step 2: The bandwidth requirements of a CR(*s*, *d*, *BR*) are split into proper line rates on a working path. We obtain the number of the line rates based on the splitting of the bandwidth requirements of a CR (*s*, *d*, *BR*), recording $\{B_{r_1}, B_{r_2}, \cdots, B_{r_{|\boldsymbol{R}|}}\}$, where B_{r_i} denotes the number of the r_i line rate. For example, suppose the CR's (*s*, *d*, *BR*) bandwidth requirement is 140 Gbps and it can be split into two line rates, 40 Gbps and 100 Gbps. The number of line rates includes $\{1_{100}, 1_{40}\}$ (i.e., one 100 Gbps line rate and one 40 Gbps line rate), run **Step 3**.

Step 3: The available spectrum resources are searched by using first fit from the lowest slot index to the highest one, where we should check all line-rate combinations on all working paths, and we then select several proper line rates on working path that guarantee the network power consumption minimized by configuring both IP router ports and the optical transponders on the source node *s* and the destination node *d* and by placing the optical regenerators for a connection request CR (*s*, *d*, *BR*) on the intermediate node along a working path. If we can find the available spectrum resources on a working path, run **Step 4,** else this CR(*s*, *d*, *BR*) is blocked.

Step 4: We allocate the spectrum resources by selecting several line rates based on $\{B_{r_1}, B_{r_2}, \cdots, B_{r_{|R|}}\}$ and the number of the slots for the r_i line rate on a working path for this CR(*s*, *d*, *BR*). If we can allocate the spectrum resources on a working path, run **Step 5,** else this CR(*s*, *d*, *BR*) is blocked.

Step 5: We should update all fiber links based on DALB before the next connection request arrives in a flexible bandwidth optical network.

Step 6: The power consumption is obtained by employing the Equation (2) to calculate the power consumption of IP router ports, optical transponders, and optical regenerators based on the transmission distance of a working path for a connection request CR(*s*, *d*, *BR*). We can repeat above steps for all connection requests, CRs(*s*, *d*, *BR*), and calculate the total power consumption one by one.

B. Traditional Dijkstra Algorithm

For comparison, we introduce the traditional Dijkstra algorithm (TD) to calculate the working path, where we do not consider the load balancing of fiber link, and split the bandwidth requirements of a connection request, CR(*s*, *d*, *BR*). We search for the spectrum resources based on $\{B_{r_1}, B_{r_2}, \cdots, B_{r_{|R|}}\}$ by first fit from the lowest slot index to the highest one, and allocate the spectrum resources on the selected working path for this CR(*s*, *d*, *BR*), and then power consumption is obtained by employing (2).

IV. SIMULATION RESULTS

We adopt the NSFNET topology to evaluate the network performance for both the DALB and TD algorithms. 10000 connection requests are generated on a data point for each experiment. Each frequency slot is 12.5 GHz spectrum width. The bandwidth requirement uniformly ranges from 60 Gbps to 200 Gbps. The unit power of optical transponder and regenerator is shown in Table 1. The unit power of an IP router port is 264.6 W for 40 Gbps (T640) in [5] and 453.6 W for 100 Gbps (T1600) in [6]. We consider two single line rates and a mixed line rate for the DALB and TD algorithms.

In Fig. 2, we observe that the blocking probability of the DALB algorithm (LB40G, LB100G, and LBMixed) is always lower than that of the TD algorithm (TD40G, TD100G, and TDMixed) under the 40 Gbps, 100 Gbps, and mixed line rates, respectively, since the DALB algorithm considers the distance-adaptive load balancing to avoid some unbalanced fiber links. Meanwhile, the DALB algorithm reduces about 17.9%, 90.0%, and 64.0% compared to the TD algorithm under 40 Gbps, 100 Gbps, and mixed line rates. In Fig. 3, we observe that the DALB algorithm consumes more power consumption compared to the TD algorithm under the 40 Gbps, 100 Gbps, and mixed line rates, respectively, since the DALB algorithm select longer distance of a working path than the TD algorithm. Therefore, in order to avoid the load balancing, the DALB algorithm should configure much more optical regenerators than the TD algorithm.

V. CONCLUSION

In this paper, we address the spectrum efficiency and power consumption problems in flexible bandwidth optical networks. A distance-adaptive load balancing algorithm is proposed to reduce the blocking probability, as well as a traditional Dijkstra algorithm is also introduced. Simulation results show that our proposed DALB algorithm can significantly reduce blocking probability but consume more power consumption compared to the TD algorithm under the 40 Gbps, 100 Gbps, and mixed line rates. We should trade off between spectrum efficiency and power consumption when we consider distance-adaptive load balancing.

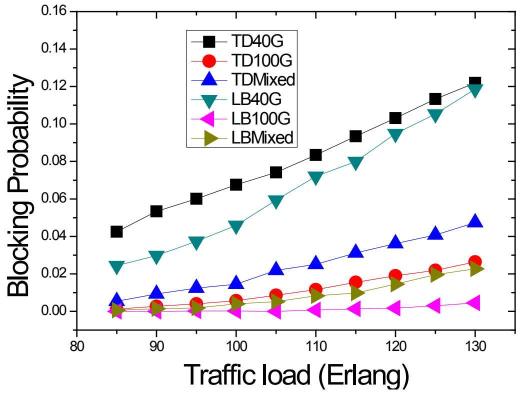

Figure.2 Blocking probability versus traffic load

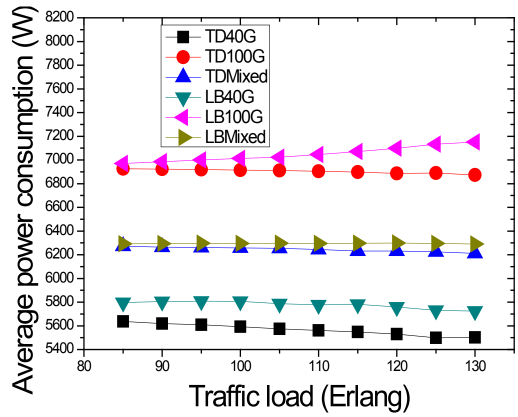

Figure.3 Average power consumption versus traffic load

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