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A Novel Multi-domain Hybrid Grooming Algorithm for Green IP over WDM Network

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Abstract. With the continuous expansion in scale and the growing Internet application, the sharply increasing electrical consumption of the network has become the bottleneck of the future networks development. Consequently, greening networks comes to the very important issue. Meanwhile, to ensure the scalability and robustness, the network is divided into multiple domains for the distributed routing and management. Therefore, it has become a hot topic on studying the multi-domain green networks. Our paper focuses on the power conservation and hybrid grooming in multi-domain IP over WDM networks by means of designing a power- and port-cost- efficient approach. This approach considers providing the power-efficient and high capacity channel or end-to-end connection for intra- or inter-domain connection demands by means of combining hybrid grooming with link-cost adjustments for computing the loose route on the higher layer logical topology. Compared with the traditional multi-domain grooming algorithm, our method has the better performances of power efficiency s.

Keywords: multi-domain IP over WDM network, power efficiency, hybrid grooming

1. Introduction

Switching demands electrically on IP layer needs marginal router power at all of immediate nodes, while promisingly, one practical method embed by an IP over Wavelength-Division-Multiplexing (WDM) network, which we call hybrid grooming, can overcome this drawback. The hybrid grooming has two key components [1]: a) the traffic grooming is utilized to migrate multiple IP-level demands into a high-capacity lightpath for electrical Transmission Ports (TPs) reduction, and b) the optical bypass ensures a lightpath be switched as a All-optical (OOO) single unit without any intermediate Optical-Electrical-Optical (OEO) conversions. This observation motivates us to focus on a novel aspect of hybrid grooming, that is the power efficiency [2]. Without losing a generality, a power-efficient IP over WDM network should be the network that can save more power by hybrid grooming at the slightly additional cost of power consumed by establishing lightpaths. Currently, there are two approaches for implementing hybrid grooming: a) single-hop hybrid grooming and b) multi-hop hybrid grooming. Our previous work [2] has demonstrated the latter is more power-efficient, and in the following parts of this paper, we directly call the approach b) as “hybrid grooming” for simplicity. On the other hand, for the purpose of security and scalability in a multi-domain optical network, the single domain operator shares scarce information resource with the others from the different domains. Furthermore, the accurate physical topology and link state information is not within the scope of inter-domain exchange. Therefore, as the previous works did [3], we need making the abstraction of global topology to form a two-layered topology structure with including an abstracted logical topology on high layer and the independent physical topologies of each domain on low layer. The full-mesh scheme is adopted in this paper to perform topology abstraction. More specially, we find at most $K, (K \geq 1)$ different shortest paths as a group for each border node pair within every domain, and then each path group is abstracted into a logical link. The path of one group also belongs to the corresponding logical link and is called the logical sub-link. Due to the tight relationship of power saved by hybrid grooming and the number of routing hops [4], each link has one unit

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of cost when we execute the full-mesh scheme above. Hereafter, on the high layer, each domain is changed into a meshed area of its own logical links and border nodes and the whole physical topology has becomes into a logical one with all of logical links, border nodes and inter-domain links; on the low layer, the whole physical topology is divided into several independent physical topologies domain-by-domain. ZHU, et. al [5] effectively reduced the cost and power consumption of translucent networks by replacing some of O/E/O 3R regenerators with the O/O/O 2R ones. For the transparent WDM optical network, ANGELO, et. al [6] and ZHANG, et. al [7] improved the network power efficiency by using sleep policy. Time-aware hybrid grooming for power minimization was proposed by CHEN, et. al [8]. They formulated an ILP model for power reduction under the static case where all connection requests with their setup and tear-down times are known in advance. However, the previous and power efficient hybrid grooming approaches mentioned above can not be applied to the multi-domain case due to the lack of global information.

2. Problem statements

2.1. Network model

The physical topology of a multi-domain optical network is denoted as $G(InterL, D)$ where $InterL$ represents the inter-domain link set and the physical topology set D records the physical topologies for $|D|$ domains and we have $D = \{D_r(BN_r, CN_r, IntraL_r) \,|\, r = 1,2,...,|D|\}$. For the physical topology of domain D_r, the notations BN_r, CN_r and $IntraL_r$ are the border node set, interior node set and the intra-domain link set, respectively. The high layer logical topology is denoted as $G_v(InterL, D_r^v)$, $r = 1,2,...,|D|$, where the logical topology set D_r^v records the logical topologies (i.e., meshed areas) for $|D|$ domains and we have $D_r^v = \{BN_r, VL_r\}$. For each meshed area of domain D_r, VL_r is the logical link set. Other important variables and notations are introduced in the following. E_t is the power consumed by each transceiver; E_{gmp} is the power consumed by each grooming matrix port; E_a is the power consumed by each optical amplifier; E_{AP} is the power consumed by each (de-) aggregating port; E_{TP} is the power consumed by each transmission port of the IP router; LP^r is the set of established lightpath segments of domain D_r; CR^r is the set of successfully groomed intra-domain demands of domain D_r; ACR^r is the set of inter-domain demands added at the domain D_r; DCR^r is the set of inter-domain demands dropped at the domain D_r; ICR is the set of successfully groomed inter-domain demands of the whole multi-domain optical network; W is the set of available wavelengths on each intra-domain link; W_C is the wavelength capacity; d is the distance between two adjacent in-line optical amplifiers; $D_{i,j}$ is the distance of the physical link (i, j), and the case $D_{i,j} \geq d$ is satisfied; $LP_{y,x,z}$ is the lightpath segment with consuming the wavelength λ_y $(1 \leq y \leq |W|)$ from node x to node z; $RB_{y,x,z}$ is the residual bandwidth of the lightpath segment $LP_{y,x,z}$; $LP_{y,x,z}^t$ is the number of demands carried by the lightpath segment $LP_{y,x,z}$; $H_{y,x,z}$ is the number of routing hops of the lightpath segment $LP_{y,x,z}$; $VL_{x,z}^r$ is the logical link between border nodes $x(x \in BN_r)$ and $z(z \in BN_r)$ of domain D_r, $VL_{x,z}^r \in VL_r$; $SVL_{x,z,m}^r$ is the m^{th} logical sub-link belong to $VL_{x,z}^r$ of domain D_r; $PH_{x,z,m}^r$ is the number of routing hops of the logical sub-link $SVL_{x,z,m}^r$; $PT_{x,z,m}^r$ is the traffic load of the logical sub-link $SVL_{x,z,m}^r$; $TB_{i,j}$ is the used bandwidth of the physical link (i, j); $|\Omega|$ is the number of elements in set Ω; Boolean variables $\gamma^{i,j}$, β^i, φ^i, $\gamma_{y,x,z}^{i,j}$ and $\gamma_{x,z,m}^{i,j,r}$ are introduced. $\gamma^{i,j} = 1$ when the physical link (i, j) is consumed by a lightpath segment; $\beta^i = 1$ when the node i is selected as the source-end node of a lightpath segment; $\varphi^i = 1$ when the node i is selected as the destination-end node of a lightpath segment; $\gamma_{y,x,z}^{i,j} = 1$ when the physical link is consumed by the lightpath segment $LP_{y,x,z}$; $\gamma_{x,z,m}^{i,j,r} = 1$ when the physical link (i, j) is consumed by the logical sub-link $SVL_{x,z,m}^r$.

2.2. Quantitative model of power efficiency

The intra-domain power efficiency reflects a correlation between power consumed by establishing lightpath segments PC^r and the power saved by using hybrid grooming SP^r of domain D_r. Among which, PC^r has the traffic independent part PC_0^r and the traffic dependent part PC_t^r, that is:

$$PC^r = PC_0^r + PC_t^r \tag{1}$$

In Eq. (1), the value of PC_0^r mainly depends on the number of lightpath segments established in the domain D_r, then we have:

$$PC_0^r = PC_{EDFA}^r + 2 \times \left|LP^r\right| \times \left(E_t + E_{gmp}\right) \tag{2}$$

In Eq. (2), the PC_{EDFA}^{r} records the total power consumed by optical amplifiers of domain D_r and can be computed in the following:

$$PC_{EDFA}^{r} = \sum_{i\in BN_r\cup CN_r} \sum_{j\in BN_r\cup CN_r, j\neq i} \left\{ \left\lceil \left(\gamma^{i,j} \cdot D_{i,j} \right) / d \right\rceil - 1 \right\} \times E_a + E_a \times \left(\sum_{i\in BN_r\cup CN_r} \beta^{i} + \sum_{i\in BN_r\cup CN_r} \varphi^{i} \right) \tag{3}$$

The first half of Eq. (3) statistics the total power consumed by in-line optical amplifiers while the other half is the total power consumed by pre- and post-amplifiers of domain D_r. For PC_t^r, the more demands processed in the domain D_r, the bigger PC_t^r, that is

$$PC_t^r = 2 \times E_{AP} \times \left| CR^r \right| + E_{AP} \times \left(\left| ACR^r \right| + \left| DCR^r \right| \right) \tag{4}$$

In this paper, the power consumed by wavelength conversion is not considered because this procedure is assumed to be performed by the pre-configured transceiver at the end node of established lightpath segment. In other words, the power consumed by transceivers, which is evaluated in Eq. (2), has involved this part of power consumed. On the other hand, the power saved by using hybrid grooming SP^r also has two main parts, they are the saved power from transmission ports of IP routers SP_{tp}^r, and OEO conversions SP_{oeo}^r:

$$SP^r = SP_{tp}^r + SP_{oeo}^r \tag{5}$$

By using the hybrid grooming in the domain D_r, the more demands carried by lightpath segments and the longer All-Optical (OOO) transmission distance bring the higher saved power SP_{tp}^r from transmission ports of IP routers, which is therefore to be presented in the following.

$$SP_{tp}^r = 2 \cdot E_{TP} \cdot \sum_{y\in W} \sum_{x\in BN_r\cup CN_r} \sum_{z\in BN_r\cup CN_r, z\neq x} LP_{y,x,z}^{t} \times H_{y,x,z} \tag{6}$$

$$H_{y,x,z} = \sum_{i\in BN_r\cup CN_r} \sum_{j\in BN_r\cup CN_r, j\neq i} \gamma_{y,x,z}^{i,j} \quad \forall x,z \in BN_r \cup CN_r,\ y \in W \tag{7}$$

The saved power from OEO conversions SP_{oeo}^r is only proportional to the OOO transmission distance of lightpath segments in the domain D_r. Then, we have:

$$SP_{oeo}^r = 2 \cdot \left(E_t + E_{gmp} \right) \cdot \sum_{y\in W} \sum_{x\in BN_r\cup CN_r} \sum_{z\in BN_r\cup CN_r, z\neq x} \left(H_{y,x,z} - 1 \right) \tag{8}$$

Without losing a generality, a more power-efficient domain should use hybrid grooming to save marginal power at the slightly additional cost of power consumption for establishing lightpath segments. Consequently, we introduce an important metric PR^r, which we call the power ratio, for evaluating intra-domain power efficiency as follows:

$$PR^r = {PC^r} \Big/ {SP^r} \tag{9}$$

Intuitively, a smaller PR^r means the higher power efficiency of domain D_r. Correspondingly, an optimized objective of this paper for power efficiency is to minimize the power ratio PR owned by the whole network, which can be described as follows:

$$Minimize\ PR = \left\{ \sum_{r=1}^{|D|} PC_0^r + 2 \times E_{AP} \times \left[\left(\sum_{r=1}^{|D|} \left| CR^r \right| \right) + \left| ICR \right| \right] \right\} \Big/ \left(\sum_{r=1}^{|D|} SP^r \right) \tag{10}$$

3. Algorithm description

After we perform the full-meshed scheme, in the meshed area mapped into the initial domain D_r, each logical link $VL_{x,z}^r$ has a logical sub-link group with an actual size of $M\,(1 \le M \le K)$. Consequently for $VL_{x,z}^r$, the values of routing hops $VLH_{x,z}^r$ and traffic load $VLT_{x,z}^r$ should be on average of the corresponding values owned by its logical sub-links. Then, we have:

$$VLH_{x,z}^r = \frac{\sum_{m=1}^{M} PH_{x,z,m}^r}{M}, \quad \forall x,z \in BN_r \tag{11}$$

$$PH_{x,z,m}^r = \sum_{i\in BN_r\cup CN_r} \sum_{j\in BN_r\cup CN_r, j\neq i} \gamma_{x,z,m}^{i,j,r}, \quad \forall x,z \in BN_r,\ m \in \{1, M\} \tag{12}$$

$$VLT^r_{x,z} = \frac{\sum_{m=1}^{M} PT^r_{x,z,m}}{M}, \quad \forall x,z \in BN_r \tag{13}$$

$$PT^r_{x,z,m} = \frac{\frac{1}{W_C \cdot |W|} \cdot \sum_{i \in BN_r \cup CN_r} \sum_{j \in BN_r \cup CN_r, j \neq i} \gamma^{i,j,r}_{x,z,m} \cdot TB_{i,j}}{PH^r_{x,z,m}}, \forall x,z \in BN_r, m \in \{1, M\} \tag{14}$$

As mentioned in our previous work [4], the saved power is proportional to both the OOO transmission distance and the number of demands carried by lightpath segments. Under this viewpoint, in order to let a loose route select more power-efficient logical links, we adjust the logical link cost according to the following principle:

$$Cost_{VL^r_{x,z}} = \frac{\alpha_1}{VLT^r_{x,z}} + \frac{\alpha_2}{VLH^r_{x,z}} \tag{15}$$

Where, α_1 and α_2 are routing hop and traffic load adjustment coefficients, respectively. Meanwhile, the conditions $0 \le \alpha_1, \alpha_2 \le 1$ and $\alpha_1 + \alpha_2 = 1$ are both satisfied. Eq. (15) tells us the logical link with more routing hops and higher traffic load has a lower cost, which makes it tend to be selected during loose route computation. Similarly, in order to let a loose route traverse more power-efficient meshed areas, we need adjusting the inter-domain link cost according to the values of power ratios in its adjacent domains. In other words, the higher power efficiency (i.e., lower power ratio) of connected domains, the lower cost will be assigned to the corresponding inter-domain link. We can infer that from Eq. (15), once the logical links in a meshed area are assigned by the lower cost, the corresponding domain will be more power efficient. Based on this principle, the inter-domain link cost is therefore to be on average of the cost owned by logical links from its adjacent domains. Then, we have:

$$Cost_{(r_1^*, r_2^*)} = \frac{\left(\sum_{x \in BN_{r_1^*}} \sum_{z \in BN_{r_1^*}} Cost_{VL^{r_1^*}_{x,z}} \right) + \left(\sum_{x \in BN_{r_2^*}} \sum_{z \in BN_{r_2^*}} Cost_{VL^{r_2^*}_{x,z}} \right)}{|VL_{r_1^*}| + |VL_{r_2^*}|} \tag{16}$$

Where, r_1^* and r_2^* are the adjacent domain index and the condition $1 \le r_1^*, r_2^* \le |D|$ is satisfied. After obtaining the link-cost adjustment-based loose path, we orderly perform intra-domain hybrid grooming within the source domain, the destination domain and the other traversed domains of the loose path. Prior to this, we need to construct an Intra-domain Wavelength Integrated Auxiliary Graph (WIAG) as our previous work devised [9] and to compute the shortest paths on WIAG. Only if all of the shortest paths are successfully found, the intra-domain hybrid grooming can be performed orderly domain-by-domain.

4. Simulation

In Fig. 1, the test topology has the multi-domain structure combined with five small-size regions, each of which has four or five border nodes. Meanwhile, 12 inter-domain links and 75 intra-domain links are configured in our test topology. The source and destination nodes of each connection demand are randomly generated and required bandwidth is always one granularity unit (i.e., OC-1). The demands arrive according to an independent Poisson process with arrival rate β and the demands' holding times are negatively exponentially distributed 1/μ, i.e., the network load is β/μ Erlang. In simulations, we set μ to 1. If we can not find eligible path for the connection, this demand is abandoned immediately. All simulation results are obtained by generating up to 5×10^3 demands. The initial number of available transceivers on each border node is assumed to be enough. By means of simulations, the optimal group of adjustment confficients can be found when the most power-efficient network status is achieved. When $|W| = 4$ and $W_C = OC - 12$, the Fig. 2 demonstrates the power efficiency values of the whole network along with the different groups of adjustment confficients (i.e., the range of traffic load adjustment confficient α_1 is from 0.1 to 0.9 and the routing hop adjustment confficient α_2 is from 0.9 to 0.1). The simulation results show that, the different arriving rates bring the different optimal groups of adjustment confficients. Moreover, in each optimal group, the value of α_1 is usually not bigger than 0.5. It means that, the power efficiency is more inclined to be effected by the routing hops not traffic load. When an optimal group of adjustment confficients is given, the power efficiency is compared between our method and the traditional Multi-Domain Grooming (MDG) algorithm [3] in the Fig. 3 under both single and multi-domain cases. The simulation results tell us that, the whole network power ratio is lower than that in the traditional multi-domain grooming approach. In other words, employing our method obtains the higher power efficiency. The reason for this is that, by means of our link cost adjustments, each loose route is able to traverse the most power-efficient domains and to consume the most power-efficient logical links in each domain.

5. Conclusion

This work has focused on performing the reasonable network resource assignment to improve the power efficiency of the whole network combined with multiple domains and proposed a novel multi-domain hybrid grooming with jiontly considering power ratio optimization and hybrid grooming. Our method not only had the advantages of power efficiency from hybrid grooming, but also improved the network resource assignment by designing the quantitative model of power ratio. Based on the quantitative model above, we performed the link-cost adjustments according to the routing hops and traffic load, which makes the loose route traverse the higher power-efficient domains and inter-domain links. Therefore, our method can provide valuable references of surpporting green grooming for the inter-domain services.

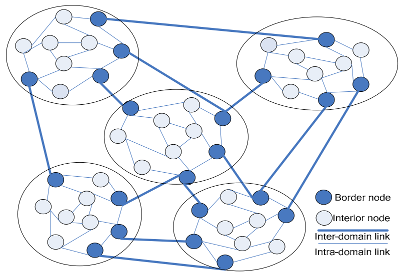

Fig. 1: .The test topology.

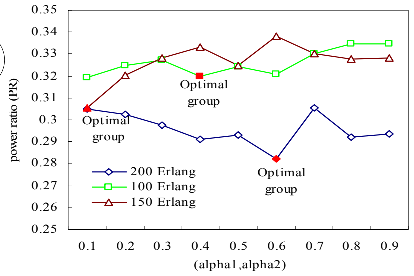

Fig. 2: The optimal coefficients group.

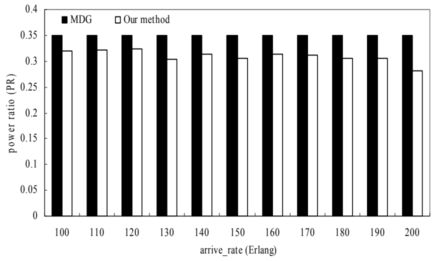

Fig. 3: Comparison of power efficiency.

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