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Static Virtual Network Mapping With Advance Reservation In Elastic Optical Networks

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***Abstract*—Many kinds of scientific applications are expected to involve data transmission, processing, and analysis at various data centers and can be represented as virtual network requests. A delay-tolerant application specifies a deadline and the corresponding virtual network request is successfully mapped as long as sufficient resources are assigned to it before the deadline, which is called advance reservation. Elastic optical networks with the capability to flexibly utilize optical bandwidth is a promising candidate for next generation backbone networks. In this paper, we address the virtual network mapping problem for static advance reservation traffic in elastic optical networks, where a set of virtual network requests are given in prior and each request requires to be scheduled within a required time window. The objective is to optimize the resource usage in the elastic optical networks. Both Integer Linear Programming (ILP) formulation and heuristics are proposed. Numerical results are presented to exhibit the effectiveness of the proposed approaches.**

***Index Terms*—elastic optical networks, virtual network mapping, advance reservation**

I. Introduction

Elastic optical networks (EONs) utilize fiber bandwidth resources to be matched up with the traffic requirements in a robust and flexible manner, which makes it a promising backbone for next generation networking. In EONs, the huge optical bandwidth is divided into fine-grained frequency slots, and only the required number of frequency slots are allocated to each request according to its bandwidth requirement. In addition, by allocating different modulation formats to different lightpaths, spectrum utilization can be increased [1], [2].

Virtualization paves way for efficient use of resources in a network. Numerous topologies with varied requirements can be placed on top of a physical network to use the required resources. Each virtual network (VN) request includes a set of virtual nodes, which are interconnected by a set of virtual links. Each virtual node specifies a required amount of computational resources, and each virtual link specifies a required amount of bandwidth resources. One important challenge for network virtualization is virtual network mapping (VNM) problem, where the resources in physical network, i.e., computational resources on physical nodes and bandwidth resources on physical links, are efficiently allocated to multiple virtual network requests. Many kinds of scientific applications involving data processing, analysis, and transmission at different data centers can be represented as virtual network requests. Some of these applications are delay-tolerant (e.g., database backup, VM migration, etc.) and can be flexibly scheduled within a time window. Such virtual network requests are called Advance Reservation virtual network requests.

A. Related Work

There exist many research papers investigating the virtual network mapping problem in EONs over the last decade. The authors of [3] address the static and dynamic versions of the virtual network mapping problem and propose both an Integer Linear Programming (ILP) formulation and heuristics. Novel algorithms are proposed in [4] to minimize the resource usage and avoid redundant multicast transmission for virtual network requests in the form of virtual optical multicast tree. The authors of [5] propose an ILP formulation and low-complexity algorithms to cost-efficiently provision virtual network functions graphs in a multi-domain EON. The static version of survivable virtual network mapping problem in EONs is investigated by the authors of [6] with the objective to minimize the working and backup resources. The authors of [7] address the dynamic version of virtual network mapping problem in software-defined EONs to reduce the blocking probability. The authors of [8] investigate the provisioning of virtual network function service chains and propose a mixed-strategy gaming based approach. An optimization model for the virtual network mapping problem is presented in [9] by assigning a large (and practical) set of combinations of paths, different modulation formats, Forward Error Correction (FEC) overheads, and baud-rates to virtual network requests. The authors of [10] propose both ILP and a delay-aware and load-balancing mapping algorithm (DALB-MA) for service function chains (SFCs) mapping in EONs. In [11], a routing, spectrum, core, and mode allocation (RSCMA) model is proposed for virtual network mapping problem over spectrally-spatially EONs while avoiding inter-core and inter-mode crosstalks. The authors of [12] propose a virtual network mapping algorithm based on the concepts of link importance degree (LID) and node importance degree (NID) for the virtual network mapping problem in space-division-multiplexing EONs. A stop-and-resume allocation scheme was proposed in [13] for dynamic virtual network mapping problem for advance reservation virtual network requests.

Advance reservation is also an attractive research topic in EONs. The dynamic version of advance reservation allocation for unicast requests is addressed in [14]. The authors of [15] propose the delayed spectrum allocation scheme to allocate network resources to anycast requests; specifically, network resources are promised to each request, but the allocation of those resources are delayed until immediately before the transmission begins. ILP formulation and heuristics are presented in [16] for immediate reservation requests and advance reservation requests in both static and dynamic operation scenarios with survivability consideration.

B. Contributions

In this paper, we address the virtual network mapping problem for static advance reservation traffic in EONs. A set of requests are given. There are virtual nodes and virtual links in each virtual network request. Each virtual node has a computing resource requirement and each virtual link has a bit rate requirement. The request specifies an earliest starting time, an latest starting time, as well as a service duration. The objective is to minimize the maximum allocated frequency slot index on any link in the physical network. Based on our best knowledge, this is the first work on static advance reservation virtual network mapping in EONs. We propose both Integer Linear Programming (ILP) formulation and an heuristic for this problem.

The paper is organized as follows. In Section II, we present the problem statement. The proposed ILP formulation and heuristics are presented in Section III. Section IV presents and discusses the numerical results. We conclude the paper in Section V.

II. Network Model and Problem Statement

We assume a slotted time system [17], where the time is segmented into a set of fixed-duration time-slots, and any unit of work that alters the availability of any network resource must occur at the beginning of a time-slot and the usage of any network resources must last for an integer multiple of the time-slot span. The physical optical network is represented as a graph $G(N, L)$, where N is the set of physical nodes, and L is the set of physical links connecting physical nodes. Each physical node n has H_n virtual machines (VM) installed. There are S frequency slots available on each physical link for each direction. The bandwidth of each frequency slot is standardized as 12.5 GHz. There are K precomputed shortest paths between each pair of physical nodes. 6 modulation formats can be assigned to the lightpaths: Binary Phase-shift keying (BPSK), Quadrature Phase Shift Keying (QPSK), 8-point Quadrature Amplitude Modulation (8QAM), 16QAM, 32QAM, and 64QAM. There is a corresponding maximum transmission reach limit for each modulation format: 3000 km, 1500 km, 750 km, 375 km, 187.5 km, and 93.75 km, respectively. For a lightpath assigned a particular modulation format, the length of the path must be no greater than the corresponding transmission reach limit. Each physical path is assigned the highest possible modulation format according to its distance and the transmission reach limits. The spectrum efficiency (Gbps/GHz) for the modulation formats are 1, 2, 3, 4, 5, and 6, respectively. There is a guardband (including G frequency slots) between two adjacent bands of allocated frequency slots on common physical links during common time slots.

There are I virtual network requests given as a set. Each virtual network request consists of a set of virtual nodes connected by virtual links. Each virtual node j of request i has a VM resources requirement h_{ij}, which is the number of VMs required. Each virtual link k of request i has a specific bit rate requirement b_{ik}. There is an earliest service starting time slot t_i and a latest service starting time slot τ_i for each virtual network request i. There is also a holding time (service duration), T_i time slots, for each request i. Each virtual node needs to be mapped to one physical node with sufficient VM resources. We assume that no more than one virtual node of a given request can be mapped to a physical node for reliability reasons. Meanwhile, each virtual link needs to be mapped to a physical path with enough frequency slots. If virtual link k of request i with b_{ik} bit rate requirement is mapped to a physical path with modulation format m, the number of required frequency slots is calculated as $\lceil b_{ik}/(12.5 * Z_m) \rceil$, where Z_m is the spectrum efficiency of modulation format m. The required VM and spectrum resources are allocated to request i from time slot x_i to $x_i + T_i - 1$, where x_i $(t_i \leq x_i \leq \tau_i)$ is the assigned starting service time slot of request i. The objective is to minimize the maximum bandwidth, i.e., the maximum frequency slot index, on any physical link at any time slot assigned to all requests.

III. Proposed Algorithms and Benchmark

A. ILP Formulation

A novel ILP formulation is proposed to minimize the maximum allocated frequency slot index in the network. There are multiple input parameters used in the ILP formulation: h_{ij} is the VM resources required by virtual node j of request i; β_{ikp} is the number of frequency slots required by request i's virtual link k if it is mapped to physical path p, which can be calculated according to the path's modulation format and virtual link's bit rate requirement; p_{src} is the source physical node of path p; p_{dst} is the destination physical node of path p; $\mu(ik)$ is the source virtual node of virtual link k in request i; $\nu(ik)$ is the destination virtual node of virtual link k in request i; $p_l \in B = \{0, 1\}$, which is 1 if path p uses physical link l; H_n is the number of VMs installed on physical node n; t_i is the earliest service starting time slot of request i; τ_i is the latest service starting time slot of request i; T_i is the holding time of request i.

The variables in the ILP include: $A_{ijn} \in B$, which is 1 if request i's virtual node j is mapped to physical node n; $Z_{ijnw} \in B$, which is 1 if request i's virtual node j is mapped to physical node n at time slot w; $F_{iw} \in B$, which is 1 if request i's starting service time is time slot w; $Y_{iw} \in B$, which is 1 if request i uses time slot w; $Q_{ikp} \in B$, which is 1 if request i's virtual link k is mapped to physical path p; $D_{iks} \in B$, which is 1 if request i's virtual link k uses frequency slot s; $R_{iks} \in B$, which is 1 if request i's virtual link k uses frequency slot s as its starting frequency slot; $\eta_{ikswl} \in B$, which is 1 if request i's virtual link k uses frequency slot s on physical link l at time slot w; and $\Lambda \in N$, the maximum frequency slot index allocated on any physical link at any time slot. This notation now allows us to formulate the following optimization problem.

$$\text{minimize} \quad \Lambda$$

s.t.

$$\sum_n A_{ijn} = 1 \quad \text{for all } i, j \tag{a}$$

$$\sum_j A_{ijn} \leq 1 \quad \text{for all } i, n \tag{b}$$

$$\sum_{ij} h_{ij} Z_{ijnw} \leq H_n \quad \text{for all } n, w \tag{c}$$

$$Z_{ijnw} \geq A_{ijn} + Y_{iw} - 1 \quad \text{for all } i, j, n, w \tag{d}$$

$$\sum_p Q_{ikp} = 1 \quad \text{for all } i, k \tag{e}$$

$$\sum_p p_{src} Q_{ikp} = \sum_n n A_{i\mu(ik)n} \quad \text{for all } i, k \tag{f}$$

$$\sum_p p_{dst} Q_{ikp} = \sum_n n A_{i\nu(ik)n} \quad \text{for all } i, k \tag{g}$$

$$\sum_w F_{iw} = 1 \quad \text{for all } i \tag{h}$$

$$\sum_w w F_{iw} \geq t_i \quad \text{for all } i \tag{i}$$

$$\sum_w w F_{iw} \leq \tau_i \quad \text{for all } i \tag{j}$$

$$\sum_w Y_{iw} = T_i \quad \text{for all } i \tag{k}$$

$$Y_{iw} - Y_{iw-1} \leq F_{iw} \quad \text{for all } i, w \tag{l}$$

$$Y_{i1} = F_{i1} \quad \text{for all } i \tag{m}$$

$$\sum_s R_{iks} = 1 \quad \text{for all } i, k \tag{n}$$

$$\sum_s D_{iks} = \sum_p \beta_{ikp} Q_{ikp} \quad \text{for all } i, k \tag{o}$$

$$D_{ik1} = R_{ik1} \quad \text{for all } i, k \tag{p}$$

$$D_{iks} - D_{iks-1} \leq R_{iks} \quad \text{for all } i, k, s \tag{q}$$

$$\sum_{ik} \eta_{ikswl} \leq 1 \quad \text{for all } s, w, l \tag{r}$$

$$\eta_{ikswl} \geq \sum_p p_l Q_{ikp} + Y_{iw} + D_{iks} - 2 \quad \text{for all } i, k, s, w, l \tag{s}$$

$$\Lambda \geq s D_{iks} \quad \text{for all } i, k, s \tag{t}$$

where the constraint (a) ensures a single physical node is assigned to each virtual node; (b) ensures no more than one virtual node of one request is mapped to the same physical node; (c) ensures VM resources at each physical node are not exceeded; (d) ensures $Z_{ijnw} = 1$ if request i's virtual node j uses physical node n at time slot w (i.e., $A_{ijn} = 1$ and $Y_{iw} = 1$); (e) ensures a single path is assigned to each virtual link; (f) and (g) ensure that the two terminal virtual nodes mapping of a virtual link matches the ending physical nodes of the physical path assigned to the virtual link; (h), (i) and (j) ensure that a single starting time slot is assigned to request i; also the request starts within its required starting time window; (k) ensures the holding time of request i is satisfied; (l) and (m) ensure a set of contiguous time slots are allocated to each request; (n) ensures that there is a single starting frequency slot assigned to each virtual link; (o) ensures enough frequency slots are allocated to each virtual link (please note that if path p is allocated to request i's virtual link k ($Q_{ikp} = 1$), the number of required frequency slots is β_{ikp}); (p) and (q) ensure that a set of contiguous frequency slot are allocated to each virtual link; (r) ensures each frequency slot on any physical link is allocated to at most one virtual link at any time slot; (s) ensures $\eta_{ikswl} = 1$ if virtual link k uses frequency slot s on physical link l at time slot w; and (t) relates the objective value to the allocated frequency slot index.

B. Proposed Heuristic

Although the ILP can provide optimal solutions, it is time consuming and only applied to small instances. Therefore, a heuristic, NL, is proposed to efficiently allocate physical resources to virtual network requests. The virtual network requests are first sorted in decreasing order according to their weights. The weight W_i of request i is calculated as $W_i = (\alpha A_i + \beta B_i) T_i$, where A_i is the total VM requirement of request i ($A_i = \sum_j h_{ij}$), B_i is the total bit rate requirement of request i ($B_i = \sum_k b_{ik}$), T_i is the holding time of request i, α and β are parameters set as $\alpha + \beta = 1$ and $\alpha/\beta = (\sum_n H_n)/(SL)$ to balance the VM and bandwidth weights. The requests are mapped one by one according to this order. For each request i under consideration, each of its possible starting service time slot x_i is tried (from t_i to τ_i), and a score Z_{x_i} is assigned to each value x_i as followings. The virtual nodes of current request i are sorted in decreasing order of their VM requirements and are mapped following this order. For each virtual node j under consideration, a set of candidate physical nodes is created and includes physical nodes that satisfy two conditions: (1) has not been assigned to any other virtual nodes of the same request i; and (2) satisfies the VM requirement of virtual node j during time period (x_i, $x_i + T_i - 1$). The candidate physical node n for virtual node j is selected (from the set) as the one has the maximum available VM resources during time period (x_i, $x_i + T_i - 1$) (the resources are calculated as $\sum_{t=x_i}^{x_i+T_i-1} H_n^t$, where H_n^t is the number of available VMs on physical node n at time slot t). Once the physical nodes are selected for all virtual nodes in request i, virtual links in request i are sorted in decreasing order of their bit rate requirements and are mapped following this order. Each virtual link k has K candidate physical paths to be mapped to (please note that there are K precomputed paths for each pair of physical nodes). The candidate physical path selected for virtual link k is the one that has sufficient frequency slot resources for virtual link k during time period (x_i, $x_i + T_i - 1$) and achieves the minimum maximum-frequency-slot-index Y_{ik} that required to be allocated to virtual link k of request i on any physical link at any time slot. The score Z_{x_i} assigned to the possible starting service time slot x_i is set as the maximum value among all virtual links' Y_{ik} values, i.e., $Z_{x_i} = \max_k Y_{ik}$. If any virtual node or virtual link is not able to be mapped successfully with starting time slot x_i, then $Z_{x_i} = \infty$. Finally, the starting service time slot assigned to request i is the one with minimum score, and the virtual nodes and virtual links are mapped accordingly. First fit spectrum assignment is adopted for frequency slot allocation. The algorithm is summarized in Algorithm 1.

Calculate the weight of each request and sort the requests in decreasing order of their weights
foreach *sorted request* i **do**
  foreach *possible starting time slot* $t_i \le x_i \le \tau_i$ **do**
    Sort the virtual nodes of request i in decreasing order of their VM requirements
    foreach *sorted virtual node* j **do**
      1. Create the set C of candidate physical nodes
      2. If $C \neq \varnothing$, select the candidate physical node n with the maximum available VM resources, otherwise, $Z_{x_i} = \infty$
    end
    Sort the virtual links of request i in decreasing order of their bit rate requirements
    foreach *sorted virtual link* k **do**
      foreach *candidate path* p **do**
        If path p has sufficient frequency slots for virtual link k, set X_{ikp} as the maximum frequency slot allocated to k on any physical link at any time slot. Otherwise, $X_{ikp} = \infty$
      end
      $Y_{ik} = \min_p X_{ikp}$
    end
    $Z_{x_i} = \max_k Y_{ik}$
  end
  Choose the starting time slot x_i with minimum value of Z_{x_i} and map the virtual nodes and virtual links accordingly.
end

Algorithm 1: NL algorithm

C. Benchmark Algorithm

Since this is the first work on this topic, we propose a benchmark algorithm, FF, to be compared with NL algorithm as followings.

The virtual network requests are mapped one by one in increasing order of their index. The current maximum occupied frequency slot index θ is initialized as 0. For each request i under consideration, each of its possible starting service time slot x_i is tried (from t_i to τ_i), and a score Z_{x_i} is assigned to each value x_i as followings. The virtual nodes of current request i are mapped one by one in increasing order of their index. For each virtual node j under consideration, a set of candidate physical nodes is created and includes physical nodes that satisfy two conditions: (1) has not been assigned to any other virtual nodes of the same request i; and (2) satisfies the VM requirement of virtual node j during time period (x_i, $x_i + T_i - 1$). The candidate physical node n for virtual node j is selected (from the set) as the one with minimum index. Once the physical nodes are selected for all virtual nodes in request i, virtual links in request i are mapped one by one in increasing order of their index. Each virtual link k has K candidate physical paths to be mapped to (please note that there are K precomputed paths for each pair of physical nodes). The K candidate physical paths are considered one by one in increasing order of their path distances. The candidate physical path is selected for virtual link k if it satisfies two conditions: (1) has sufficient frequency slot resources for virtual link k during time period (x_i, $x_i + T_i - 1$), and (2) the maximum required frequency slot index allocated to virtual link k on the candidate path at any time slot is no greater than θ. If no candidate path satisfies the two conditions, virtual link k is mapped to the candidate physical path that achieves the minimum maximum-frequency-slot-index Y_{ik} that required to be allocated to virtual link k of request i on any physical link at any time slot. The score Z_{x_i} assigned to the possible starting service time slot x_i is

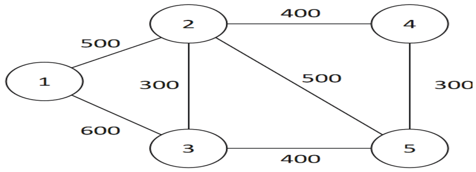

Fig. 1. 5-node Network Topology

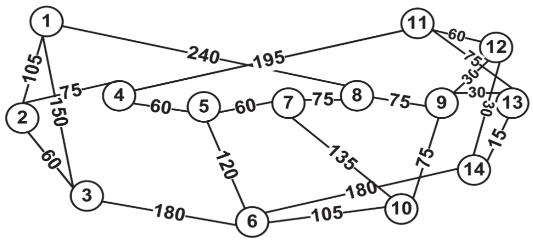

Fig. 2. 14-node NSF Network Topology

set as the maximum value among all virtual links' Y_{ik} values, i.e., $Z_{x_i} = \max_k Y_{ik}$. If any virtual node or virtual link is not able to be mapped successfully with starting time slot x_i, then $Z_{x_i} = \infty$. If $Z_{x_i} \leq \theta$, then x_i is assigned to request i, the virtual nodes and virtual links are mapped accordingly, and the algorithm moves forward to map the next request. If the scores with all possible starting service time slots are greater than θ, the starting service time slot assigned to request i is the one with minimum score, then θ is updated to the minimum score, and the virtual nodes and virtual links are mapped accordingly. First fit spectrum assignment is adopted for frequency slot allocation. The algorithm is summarized in Algorithm 2.

IV. Simulation Results

There are two network topologies for simulations, a small 5-node network, and the 14-node NSF network topology (NSFNET) as shown in Figs. 1 and 2. The number of pre-computed shortest paths between each pair of physical nodes is set as 2. Each request includes 3 virtual nodes requiring 1, 2, 3 VMs, respectively. The holding time is set as 3 for all requests. For the small 5-node network, there are 10 frequency slots available on each physical link at each time slot, 10 VMs equipped at each physical node at each time slot, and 10 total available time slots. There are three virtual links in each request requiring 10, 20, 30 Gbps bit rate, respectively. The earliest starting time slot is 2 and latest starting time slot is 4 for all requests. For the 14-node NSF network, there are 320 frequency slots on each physical link at each time slot, 500 VMs equipped at each physical node at each time slot, and 500 total available time slots. There are three virtual links in each request requiring 100, 150, 200 Gbps bit rate, respectively. The earliest starting time slot is randomly selected in the range $(1, 100)$, and latest starting time slot is set as earliest starting time slot plus 10 for all requests.

For the small 5-node network, Fig. 3 indicates that the benchmark FF exhausts the bandwidth resources for more than 5 requests, therefore there is no result from FF with the number of requests being 6. The NL saves up to 40% bandwidth compared with FF. Furthermore, the ILP saves up to 60% bandwidth compared with NL. For the 14-node NSFNET network, the ILP was too complex, so we only compare NL and FF. As shown in Fig. 4, NL provides up to 53.8% bandwidth reduction compared to the benchmark FF.

Sort the requests in increasing order of their index
The current maximum occupied frequency slot index θ on any physical link at any time slot initialized as 0
foreach *request* i **do**
  foreach *possible starting time slot* $t_i \leq x_i \leq \tau_i$ **do**
    Sort the virtual nodes of request i in increasing order of their index
    foreach *sorted virtual node* j **do**
      1. Create the set C of candidate physical nodes
      2. If $C \neq \varnothing$, select the candidate physical node with minimum index, otherwise, $Z_{x_i} = \infty$
    end
    Sort the virtual links of request i in increasing order of their index
    foreach *sorted virtual link* k **do**
      foreach *candidate path* p **do**
        If path p has sufficient frequency slots for virtual link k, set X_{ikp} as the maximum frequency slot allocated to k on any physical link at any time slot. Otherwise, $X_{ikp} = \infty$. If $X_{ikp} \leq \theta$, candidate path p is selected for virtual link k, $Y_{ik} = X_{ikp}$, continue to consider the next virtual link mapping
      end
      $Y_{ik} = \min_p X_{ikp}$
    end
    $Z_{x_i} = \max_k Y_{ik}$, if $Z_{x_i} \leq \theta$, starting time slot x_i is selected for request i, map the virtual nodes and virtual links accordingly, continue to next request
  end
  Choose the starting time slot x_i with minimum value of Z_{x_i}, $\theta = Z_{x_i}$, and map the virtual nodes and virtual links accordingly.
end

Algorithm 2: FF algorithm

V. Conclusions

In this paper, we investigate advance reservation virtual network mapping for static traffic in Elastic Optical Networks

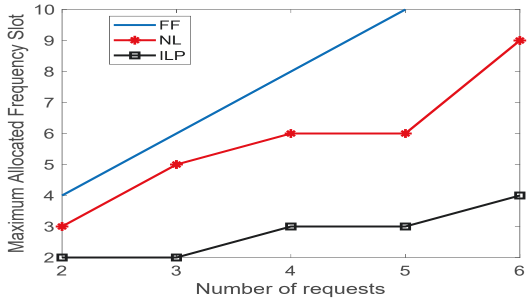

Fig. 3. Maximum frequency slot vs. number of requests in 5-node network topology

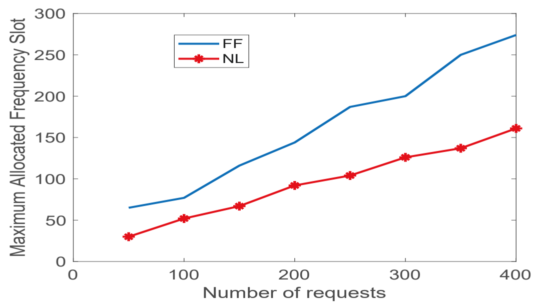

Fig. 4. Maximum frequency slot vs. number of requests in 14-node NSF network topology

with the objective to minimize the maximum allocated frequency slot index on any physical link at any time slot assigned to all requests. Both ILP and a low complexity algorithm are proposed. Simulation results show that the proposed algorithm saves up to 53.8% in bandwidth compared with the benchmark algorithm.

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