Virtual Network Reconfiguration in Optical Cloud Substrates

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Abstract: This paper studies reconfiguration design for cloud-based virtual network services mapped over optical substrates. A novel scheme is proposed to improve resource efficiency and its results are analyzed versus some existing strategies.

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I. Introduction

The rapid uptake of new cloud-computing applications is driving the need to provision client services over geographically-dispersed resources. In particular, network virtualization has become a necessity as it allows operators to provision dedicated client *virtual networks* (VN) over base (optical) substrate networks and data-centers. A typical VN request consists of a set of VN nodes interconnected by a set of VN links, i.e., each VN node requests a given amount of storage and computing resources (from the data-center) and each VN link requests a given amount of bandwidth connectivity between its endpoint VN nodes. To support this, a range of VN mapping algorithms have been designed to assign VN nodes to distinct physical substrate nodes and VN links to underlying (optical) connections. As this mapping problem is NP-hard [2], most schemes are heuristics-based strategies which try to maximize revenue or reduce costs [1],[2].

Nevertheless, most VN mapping schemes give high resource fragmentation in the network substrate, particularly when user requests arrive/depart in a dynamic manner. Hence VN *reconfiguration* strategies have also been proposed to improve resource efficiency. For example, [1] periodically migrates selective VNs based upon overloaded substrate fiber links. Meanwhile [2] periodically checks and re-computes VN links for active VN requests with longer residual lifetimes. Overall, these periodic strategies are classified as *proactive* and have relatively high computational overheads and migration costs. Hence other *reactive* strategies have also been proposed to perform VN reconfiguration after setup failures. For example, [3] presents a *virtual network reconfiguration* (VNR) scheme to migrate one VN node (and its VN links) to control migration costs, i.e., versus migrating a whole VN topology as in [1]. Simulations show good blocking and migration cost reduction with this reactive approach over some proactive schemes. However the VNR scheme uses a greedy approach as it only migrates a minimum number of VN nodes to accept the rejected VN request. Hence this scheme can cause increased congestion (blocking) at bottleneck links.

To address these shortcomings, this paper presents an improved reconfiguration scheme for VN mapping over optical networks. The scheme uses a reactive approach to perform multiple (batch) reconfigurations and achieve improved blocking and migration cost reduction. The paper is organized as follows. Section II details the VN reconfiguration problem followed by the proposed reconfiguration solution. Performance results are then presented in Section III along with conclusions and future work directions.

II. Reconfiguration Approach

A novel VN reconfiguration scheme is now presented. Consider the requisite notation first. The base optical substrate is modeled as an undirected graph, $\boldsymbol{G}_s=(\boldsymbol{V}_s,\boldsymbol{E}_s)$, where $\boldsymbol{V}_s$ is the set of substrate nodes and $\boldsymbol{E}_s$ is the set of substrate links. Each substrate node $v_s \in \boldsymbol{V}_s$ has varying amounts of free/available computing and storage resources, generically represented by $R(v_s)$. Meanwhile each substrate fiber link $e_s \in \boldsymbol{E}_s$ has a variable amount of available capacity given by $B(e_s)$. Now each client VN request is given by an undirected graph, $\boldsymbol{G}_v=(\boldsymbol{V}_v,\boldsymbol{E}_v)$, where $\boldsymbol{V}_v$ is the set of VN nodes and $\boldsymbol{E}_v$ is the set of VN links. Here each VN node $v_v \in \boldsymbol{V}_v$ requires $r(v_v)$ in nodal resources and each VN link $e_v \in \boldsymbol{E}_v$ requires $b(e_v)$ in bandwidth capacity. Without loss of generality, it is also assumed that all links have capacity B_c (wavelengths). Furthermore, a VN mapping requires that a VN node v_v be assigned to a specific substrate node v_s, i.e., mapping denoted as $<v_v,v_s>$. Likewise, each VN link e_v also has two end-points, denoted by the pair (v_v, v_v'). Using this notation, a sample 8-node optical substrate network is shown in Fig. 1a, where the values over the links (nodes) denote the available bandwidth (nodal resources) levels. A sample 4-node VN request is also shown in Fig. 1b, and this request can be mapped (embedded) over the physical substrate topology.

The proposed solution uses a reactive approach and is termed as the *multiple VN node reconfiguration* (MVNNR) scheme. This algorithm is invoked after failure of a regular VN setup attempt and migrates a subset of VN nodes (from the set of existing mapped VN requests) to relieve congestion on overloaded optical substrate links. The algorithm is detailed in Fig. 2 and starts by grouping all congested substrate links into a *congestion set*, $\boldsymbol{S}$, based on *relative* bandwidth loading, i.e., $\boldsymbol{S}=\{e_s \in \boldsymbol{E}_s \mid B(e_s) \le \alpha B_c\}$, where α is a relative usage threshold, $0 \le \alpha \le 1$. Using this set, a ranking metric is defined for each VN node q as:

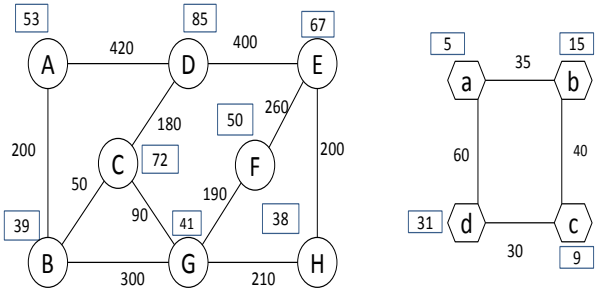

Figure 1: a) substrate network, b) sample VN request topology

$$k = A \times T \qquad \text{Eq. (1)}$$

where A is the number of congested links in $\boldsymbol{S}$ used by VN links attached to q, and T is the residual lifetime of the VN request with node q. Note that the lifetime is incorporated here since studies have shown the benefit of using it to reduce resource fragmentation over the long term [2]. These costs, k, are then used to sort all VN nodes in the active requests in decreasing order and generate a *candidate migration list*, $\boldsymbol{Q}$ (Fig. 2). The MVNNR scheme then loops through the first R VN nodes in $\boldsymbol{Q}$ and attempts to migrate each (along with its set of adjacent VN links) in sequence. Namely, a further candidate set of *substrate* nodes, $\boldsymbol{L}$, is generated here for each VN node $q_i \in \boldsymbol{Q}$ based upon two criteria, i.e., if the substrate node is not already mapped to another VN node in the same request *and* there are sufficient nodal resources (lines 9-12, Fig. 2). The algorithm then uses this candidate set to select a new substrate mapping for VN node q_i. Consider the details here.

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1. Construct congested link set S and VN node migration list
   Q containing all VN nodes of all active VN requests
2. For each q∈Q, compute migration metric k using Eq. (1)
3. Sort VN nodes in Q in decreasing order using k
4. for i = 1 to R
5.     Select i-th VN node q_i ∈ Q (q_i belongs to request G_v)
6.     n=record of current node/link mapping for <q_i, v_s>, i.e.,
       where v_s is allocated to q_i
7.     Release resource for record n in G_s
8.     Set candidate substrate node list L to empty
9.     for each v_s∈V_s
10.        if (no other VN nodes in G_v mapped to v_s)
11.            if (R(v_s)≥r(q_i))
12.                Insert v_s to L
13.    m=call MVN (q_i,G_v,L)
14.    if (m!=NULL)
15.        Migrate q_i according record m, reserve resource for
           record m in G_s
16.    else
17.        Reserve resource for record n in G_s
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Figure 2: MVNNR algorithm

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1.  Given VN node q_i in G_v and substrate node list L
2.  Initialize s_min=+∞, m={}
3.  for (each v_s∈L)
4.      Create substrate graph G_s copy, denoted by G_t
5.      l=SUCCESS
6.      for each v_v is adjacent to q_i in G_v
7.          result=compute minimum cost substrate fiber
            path p for virtual link (v_v, q_i) in G_t
8.          if(result=FAIL)
9.              l=FAIL
10.             break
11.         else
12.             reserve bandwidth for p in G_t
13.     if (l=SUCCESS)
14.         s=compute stress for <q_i,v_s> using Eq. (2)
15.         if (s <s_min)
16.             Update s_min = s
17.             m=record of node/link mapping for <q_i, v_s>
18. return m
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Figure 3: MVN sub-algorithm

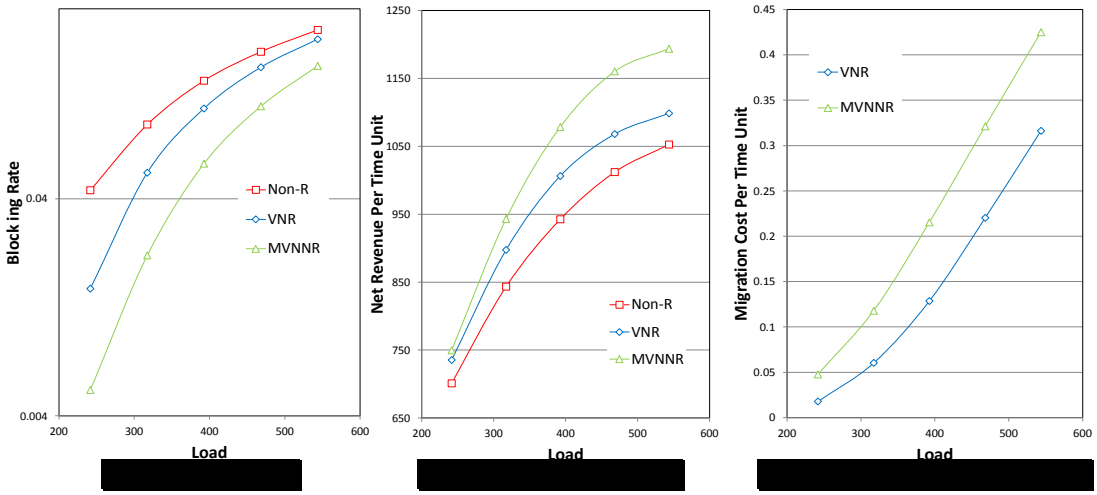
The psuedocode for substrate node selection is shown in Fig. 3 and termed as the *migrate virtual node* (MVN) sub-algorithm, called from main MVNNR algorithm (line 13, Fig. 2). This selection basically looks at each substrate node $v_s \in \boldsymbol{L}$ and tries to map all the attached VN links, i.e., connections to neighboring VN nodes for the given node $q_i \in \boldsymbol{Q}$. Note that this computation is done over a temporary working copy, $\boldsymbol{G}_t$, of the main substrate graph, $\boldsymbol{G}_s$. Here, if feasible substrate connection paths can be computed for all VN links here, then the associated substrate node v_s is deemed a valid mapping node. However in order to minimize congestion on substrate optical links, the algorithm also computes a stress metric, s, for all valid node mappings and selects the substrate node with the lowest stress from all nodes in $\boldsymbol{L}$, i.e., lines 13-17, Fig. 3. Specifically, this stress value is defined as:

$$\boldsymbol{s} = \frac{\mathbf{1}}{\boldsymbol{B_a + \varepsilon}} \qquad \text{Eq. (2)}$$

where B_a is the average residual bandwidth of substrate paths allocated for all attached VN links for q_i and ε is a small value used to avoid division errors. Also note that the shortest-path computation step (i.e., line 7, Fig. 3) can either use fixed (operator-specified) or dynamic weights for links in the substrate graph $\boldsymbol{G}_s$. In particular, the latter case can be used to implement load-balancing over the substrate network by assigning weights as inversely-proportional to available capacity. In addition, special data structures are also needed to record the mapping information for a VN node and its attached VN links, i.e., as per line 6 in MVNNR (Fig. 2) and line 17 in MVN (Fig. 3).

III. Performance Evaluation

The MVNNR reconfiguration scheme is tested using custom-built *OPNET Modeler*^{TM} models. Tests are done for a 24-node optical topology where substrate nodes have 100 units of resource capacity (computing, storage) and substrate optical links have 100 wavelengths. Meanwhile, VN requests are generated by composing randomized graph topologies with 4-7 nodes each and an average node degree of 2.6. The requested VN node capacities are also uniformly-distributed between 1-10 units and VN link capacities between 1-2 wavelengths. Furthermore, VN request holding and inter-arrival times are exponentially distributed with means μ=600 sec and λ, respectively (and λ varied according to input load). Here all tests are done for 100,000 VN requests and fixed unity weights are used for all links in the shortest-path computation phase, i.e., to minimize hop count/resource utilization. Now the actual input loads are measured using *modified* Erlang metric that takes into account VN request sizes, i.e., specified as a product of the average number of VN links and μ/λ, as introduced in [5]. Finally, the *non-survivable virtual infrastructure mapping* (NSVIM) scheme in [4] is used as the base VN mapping algorithm, and the VNR scheme from [3] is also tested for comparison. This NSVIM algorithm uses a *single-stage* approach which maps a VN node to a substrate node along with its attached VN links in the same step/iteration.



The results for VN request blocking rates as shown in Fig. 4, where the baseline "non-reconfiguration" NSVIM scheme is labeled as "*Non-R*". These findings clearly show much better performance with the reconfiguration schemes, e.g., up to 88% lower rejection rates at low-medium loads. More importantly, the proposed MVNNR scheme gives 66% lower blocking than the VNR scheme, validating the benefits of migrating multiple VN nodes. Next, long term net revenues are plotted in Fig. 5, and these findings clearly show much higher operator income with the reconfiguration schemes, i.e., 13% more at medium-to-high loads. The MVNNR scheme also gives higher net revenues than the VNR scheme (almost 10%) due to its lower blocking performance. Finally, Fig. 6 plots the long-term VN reconfiguration costs for the two reconfiguration schemes. Akin to [3], this value is measured as the total cost of migrating all VN nodes and their attached links, i.e., which is given by a weighted sum of the number of migrated VN nodes and VN links. As expected, the proposed MVNNR solution gives higher costs, particularly at heavier loads, by up to 30%. Nevertheless, this increase is notably offset by the increase in revenues, i.e., Fig. 5.

This paper presents a novel reactive VN reconfiguration strategy for optical networks that migrates multiple nodes to minimize substrate congestion. Simulations show much-improved blocking and higher net revenues versus existing schemes. Ongoing efforts are extending this work for survivable VN design.

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