2009 International Conference on Computer Engineering and Applications
IPCSIT vol.2 (2011) © (2011) IACSIT Press, Singapore

A New Survivable Heuristic Algorithm Based on Hamiltonian Cycle Protection in Multi-Domain Optical Networks

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Abstract. This paper proposes a new algorithm, Multi-domain Hamiltonian Cycle Protection (MHCP) to tolerate single-fiber link failure in multi-domain optical networks. In MHCP, we develop Local Hamiltonian Cycle (LHC) in each single-domain and Globe Hamiltonian Cycle (GHC) in multi-domains to protect the intra-link and inter-link failures, respectively. Simulation results show that, compared to previous algorithm, MHCP can obtain better resource utilization ratio and lower blocking probability.

Keywords: optical networks, survivability, multi-domain, Hamiltonian cycle protection, virtual topology

1. Introduction

In WDM optical networks, a wavelength channel has the transmission rate of several gigabits per second, so that the failures may lead to a lot of traffic blocked. Therefore, survivability in WDM optical networks is an important issue. The methods in survivability mainly include protection and restoration. Since protection is easier to be configured and has faster recovery time than restoration, most previous work focused on protection [1, 2]. Protection generally includes path-based protection, link-based protection, and segment-based protection, where path-based protection can perform better resource utilization but slower recovery time than link-based protection and segment-based protection.

With the appearance of General Multi-Protocol Label Switching (GMPLS) [3] and the development of Automatic Switched Optical Networks (ASON), the seamless convergence between IP and optical networks can be realized. Same with Internet, current optical networks have been actually divided into multiple domains and each domain has its own provider and management policy for independent failure restoration. Therefore, the development of multi-domain optical networks is the trend of next-generation intelligent optical networks, and survivability in multi-domain optical networks has become an important issue [4-7].

In [5], the authors proposed an extended shared-path protection (ESPP) algorithm in multi-domain optical networks based on the full mesh abstracted virtual topology [4]. In [6, 7], the authors proposed a sub-path-based protection algorithm, in which each connection is first assigned to an inter-working path, then the working path is divided to several working segments based on the domain range, and finally each working segment is assigned to a link-disjoint backup segment path within the same domain. However, the protection algorithms in [5-7] are all based on path-shared protection (PSP) method. In previous work [8], through analysis and simulation results, the authors presented that Hamiltonian Cycle Protection (HCP) can obtain better performances than PSP in single-domain. Therefore, we consider extend the HCP from single-domain protection to multi-domain protection to obtain better performances than PSP-based algorithm. Although the authors in [9] suggested the idea of HCP in multi-domain optical networks by Integer Linear Programming (ILP) solution, they did not propose efficient heuristic algorithms and also did not consider the virtual topology of multi-domain optical networks.

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In this paper, we propose a new heuristic algorithm called Multi-domain Hamiltonian Cycle Protection (MHCP) to tolerate single-fiber link failure in multi-domain optical networks. We present the idea of Local Hamiltonian Cycle (LHC) based on the physical topology of each single-domain and Globe Hamiltonian Cycle (GHC) based on the virtual topology of multi-domains to protect the single intra-fiber link and inter-fiber link failures, respectively. We also design the link-cost functions to achieve the load balancing and proper links selection in computing the working path for each connection request. Compared to previous protection algorithm, MHCP can obtain better resource utilization ratio and lower blocking probability.

2. Problem Statement

2.1. Network Model

The given multi-domain optical network is denoted by $G(N, W, InterL, D)$, where N is the set of network nodes, W is the set of wavelengths in each fiber link, $InterL$ is the set of inter-fiber links between different domains, and D is the set of topologies of multi-domain networks defined as $D=\{D_k(N_k, IntraL_k)|k=1,2,...\}$ in which N_k is the set of network nodes in domain k and $IntraL_k$ is the set of intra-fiber links in domain k. We assume each connection requires the bandwidth of one wavelength, and each network node has full wavelength conversion capability. In domain k, a Hamiltonian cycle LHC_k which is composed of intra-fiber links is generated based on the physical topology of domain k to provide the protection for intra-failures. In multi-domains, a GHC which is composed of inter-fiber links and virtual-links is generated based on the virtual topology of multi-domains to provide the protection for inter-failures, where the virtual-link VL_k is the map of LHC_k. All virtual-links compose a set $VL=\{VL_k|k=1,2,...\}$. The shortest path algorithm, i.e., Dijkstra's algorithm, is applied to compute the route. The following notations are introduced.

CR_r : Connection request r.

WP_r : Working path of CR_r.

NW_j : Number of working wavelengths on link j.

NF_j : Number of free wavelengths on link j.

O_{Lk} : Set of on-cycle links which are intra-fiber links traversed by LHC_k in domain k.

S_{Lk} : Set of straddling links which are intra-fiber links not traversed by LHC_k in domain k.

NB_{Lk} : Number of backup wavelengths on each on-cycle link on LHC_k in domain k.

O_G : Set of on-cycle links which are inter-fiber links traversed by GHC in multi-domains.

S_G : Set of straddling links which are inter-fiber links not traversed by GHC in multi-domains.

NB_G : Number of backup wavelengths on each on-cycle link on GHC in multi-domains.

$|\phi|$: Number of elements in set ϕ.

2.2. Backup Wavelengths Assignment

The HCP is proposed in [8, 9] to achieve fast restoration and simple management. In order to achieve HCP, there must be at least a Hamiltonian cycle in network. Fortunately, we can find the Hamiltonian cycles in most current optical backbone networks, e.g., US National, China CERNET, NJLATA, ECNET, etc.

$$NB_{Lk} = \max\left\{\max\left(NW_j \,|\forall j \in O_{Lk}\right), \max\left(\frac{NW_j}{2}|\forall j \in S_{Lk}\right), \max\left(\frac{NW_j}{2}|\forall j \in O_G\right), \max\left(\frac{NW_j}{4}|\forall j \in S_G\right)\right\} \quad (1)$$

$$NB_G = \max\left\{\max\left(NW_j \,|\forall j \in O_G\right), \max\left(\frac{NW_j}{2}|\forall j \in S_G\right)\right\} \quad (2)$$

In single-fiber link failure, the backup wavelengths needed on each on-cycle link on $LHC_k(\forall k \in [1,|D|])$ can be obtained according to (1), where the backup wavelengths are determined by four parts: 1) the maximum value of working wavelengths on on-cycle links on LHC_k; 2) the maximum value of half of working wave-lengths on straddling links on LHC_k; 3) the maximum value of half of working wavelengths on straddling links on GHC; 4) the maximum value of quarter of working wavelengths on straddling links on GHC. The backup wavelengths needed on each on-cycle link on GHC can be obtained according to (2), where the backup wavelengths are determined by two parts: 1) the maximum value of working wavelengths on on-cycle links on GHC; 2) the maximum value of half of working wavelengths on straddling links on GHC.

An illustration is in Fig. 1 for Hamiltonian cycle protection in multi-domains, where gateway nodes are A2, A4, B1, B3, C1 and C3, and inter-fiber links are A2-B1, A4-C1, B1-C1 and B3-C3. In Fig. 1, LHC_A, LHC_B and LHC_C are respectively A1-A2-A3-A4, B1-B2-B3-B4 and C1-C2-C3-C4, which can provide the protection for any single intra-link failure in single-domain. For example, in domain A, for on-cycle link A1-A2 failure, the working traffic on it can be protected by the route A1-A4-A3-A2; for straddling link A1-A3 failure, the working traffic on it can be protected by two routes, A1-A2-A3 and A1-A4-A3. Therefore, to protect the single intra-fiber link failure, the backup wavelengths needed on each on-cycle link on LHC are determined by the maximum value of working traffic on on-cycle links on LHC and the maximum value of half of working traffic on straddling links on LHC.

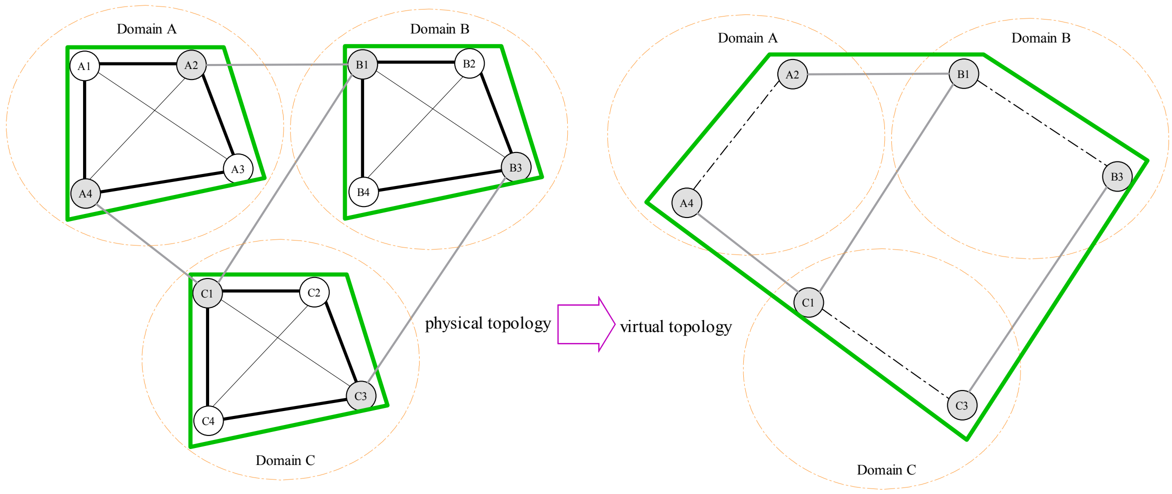


Fig. 1: Illustration of Hamiltonian cycle protection in multi-domains

If we abstract each local Hamiltonian cycle to a virtual link between gateway nodes, we can obtain a globe virtual topology for multi-domains, which can be viewed by each single-domain. In Fig. 1, LHC_A, LHC_B and LHC_C are abstracted to the virtual links A2-A4, B1-B3 and C1-C3, respectively. Therefore, GHC is A4-A2-B1-B3-C3-C1 that can provide the protection for any single inter-link failure in multi-domains. For example, for on-cycle link A2-B1 failure, the working traffic on it can be protected by the virtual route A2-A4-C1-C3-B3-B1; for straddling link B1-C1 failure, the working traffic on it can be protected by two different virtual routes, B1-A2-A4-C1 and B1-B3-C3-C1. Then, to protect the single inter-fiber link failure, the backup wavelengths needed on each on-cycle link on GHC are determined by the maximum value of working traffic on on-cycle links and the maximum value of half of working traffic on straddling links on GHC. Here, on-cycle links and stranding links do not include virtual links since each virtual link is the map of routes on LHC that has been protected in each single-domain.

It is obvious that each virtual link is the map of two different routes on LHC. For above example, we focus on domain A, where virtual link A2-A4 is the map of two routes A2-A1-A4 and A2-A3-A4. In GHC, for on-cycle link A2-B1 failure, the working traffic on it can be actually carried by two routes A2-A1-A4 and A2-A3-A4 in domain A; for stranding link B1-C1 failure, the half of working traffic on it also can be actually carried by two routes A2-A1-A4 and A2-A3-A4 in domain A. Then, to protect single inter-fiber link failure, the backup wavelengths needed on each on-cycle link on LHC are also determined by the maximum value of half of working traffic on on-cycle links on GHC and the maximum value of quarter of working traffic on straddling links on GHC.

2.3. Working Path Selection

The working path selection is divided to intra-domain routing and inter-domain routing. For each connection request, if the source node and destination node belong to the same domain, we perform the intra-domain routing; otherwise, we perform the inter-domain routing.

In intra-domain routing for connection request from source node X and destination node Y both in domain k, we first adjust the cost for each link j according to (3) and then compute a least-cost working path from node X and node Y based on the physical topology of domain k.

$$Cost_j = \begin{cases} +\infty, & \text{if } (j \in \text{IntraL}_k, NF_j < 1) \text{ or } (j \notin \text{IntraL}_k) \\ \frac{|W|+1-NF_j}{|W|} \cdot C_j^*, & \text{if } (j \in \text{IntraL}_k, NF_j \geq 1) \end{cases} \quad (3)$$

$$C_j^* = \begin{cases} +\infty, & \text{if } (j \in O_{Lk}, NW_j + 1 > NB_{Lk} + NF_f, \exists f \in O_{Lk}) \text{ or } \left(j \in S_{Lk}, \left\lceil \frac{NW_j+1}{2} \right\rceil > NB_{Lk} + NF_f, \exists f \in O_{Lk}\right) \\ & \text{or } \left(j \in O_G, \left\lceil \frac{NW_j+1}{2} \right\rceil > NB_{Lk} + NF_f, \exists f \in O_{Lk}\right) \text{ or } \left(j \in S_G, \left\lceil \frac{NW_j+1}{4} \right\rceil > NB_{Lk} + NF_f, \exists f \in O_{Lk}\right) \\ 1, & \text{otherwise} \end{cases} \quad (4)$$

We can see that in (3) the costs of links that have no enough free wavelengths and do not belong to domain k will be set to infinite while the costs of links that have enough free wavelengths will be set to finite values according to the load balancing idea; that is, more free wavelengths mean less link-costs, and then the working path will be favourable for traversing these links and the assigned working wavelengths can be more uniformly distributed to all links. Then, the load will be more balance. In (4), if the working path traverses link j and the sum of free and backup wavelengths on on-cycle link f are not enough, link j will have infinite cost; otherwise, if the working path traverses link j and the sum of free and backup wavelengths of some on-cycle link f are enough, link j will have finite cost. Therefore, it is obvious that the link-cost function can encourage the load balancing and proper links selection to compute the working path.

In inter-domain routing for connection request from source node X in domain k1 and destination node Y in domain k2, first we perform the intra-domain routing from node X to a random gateway node G1 based on the physical topology of domain k1 to obtain a sub-working path SW1, second we compute a sub-working path SW2 from node G1 in domain k1 to a random gateway node G2 in domain k2 based on the full mesh abstracted topology in [4], third we perform the intra-domain routing from node G2 to node Y based on the physical topology of domain k2 to obtain a sub-working path SW3, and finally we combine SW1, SW2 and SW3 to form the whole inter-domain working path.

3. Heuristic Algorithm

The heuristic steps of proposed MHCP algorithm are presented as follows:

Input: Network topology; Q connection requests; $r \leftarrow 0$

Output: The total resources consumption T

Step 1: Find LHC for each single-domain based on its physical topology and GHC for multi-domains based on the virtual topology by some off-line manner. Let $NB_{Lk} \leftarrow 0 (\forall k \in [1, |D|])$ and $NB_G \leftarrow 0$.

Step 2: If $r \geq Q$, go to Step 6; otherwise, go to Step 3.

Step 3: If the source node and destination node are in the same domain, execute the intra-domain routing; otherwise, execute the inter-domain routing. If WP_r can be found, go to Step 4; otherwise, go to Step 5.

Step 4: Record WP_r , let $NW_j \leftarrow NW_j + 1 (\forall j \in WP_r)$, update $NB_{Lk} (\forall k \in [1, |D|])$ and $NB_G \leftarrow 0$ according to (1) and (2), let $r \leftarrow r + 1$, and go back to Step 2.

Step 5: Block this connection request, let $r \leftarrow r + 1$, and go back to Step 2.

Step 6: Return the total resources consumption as follows:

$$T = NB_G \cdot |O_G| + \sum_{\forall j \in InterL} NW_j + \sum_{\forall k \in [1,|D|]} NB_{Lk} \cdot |O_{Lk}| + \sum_{\forall k \in [1,|D|]} \sum_{\forall j \in IntraL_k} NW_j \quad (5)$$

In the above processes, the Hamiltonian cycles can be obtained by some off-line manner in Step 1, so that the time complexity for this is ignored. We mainly consider the time complexity of computing the working path which depends on the times of running Dijkstra's algorithm whose time complexity is $O(|N|^2)$. In step 3, in the worst case, MHCP will run three times of Dijkstra's algorithm to compute the inter-domain working path for each connection request. Therefore, the time complexity for each connection request in MHCP is approximately $O(3|N|^2)$.

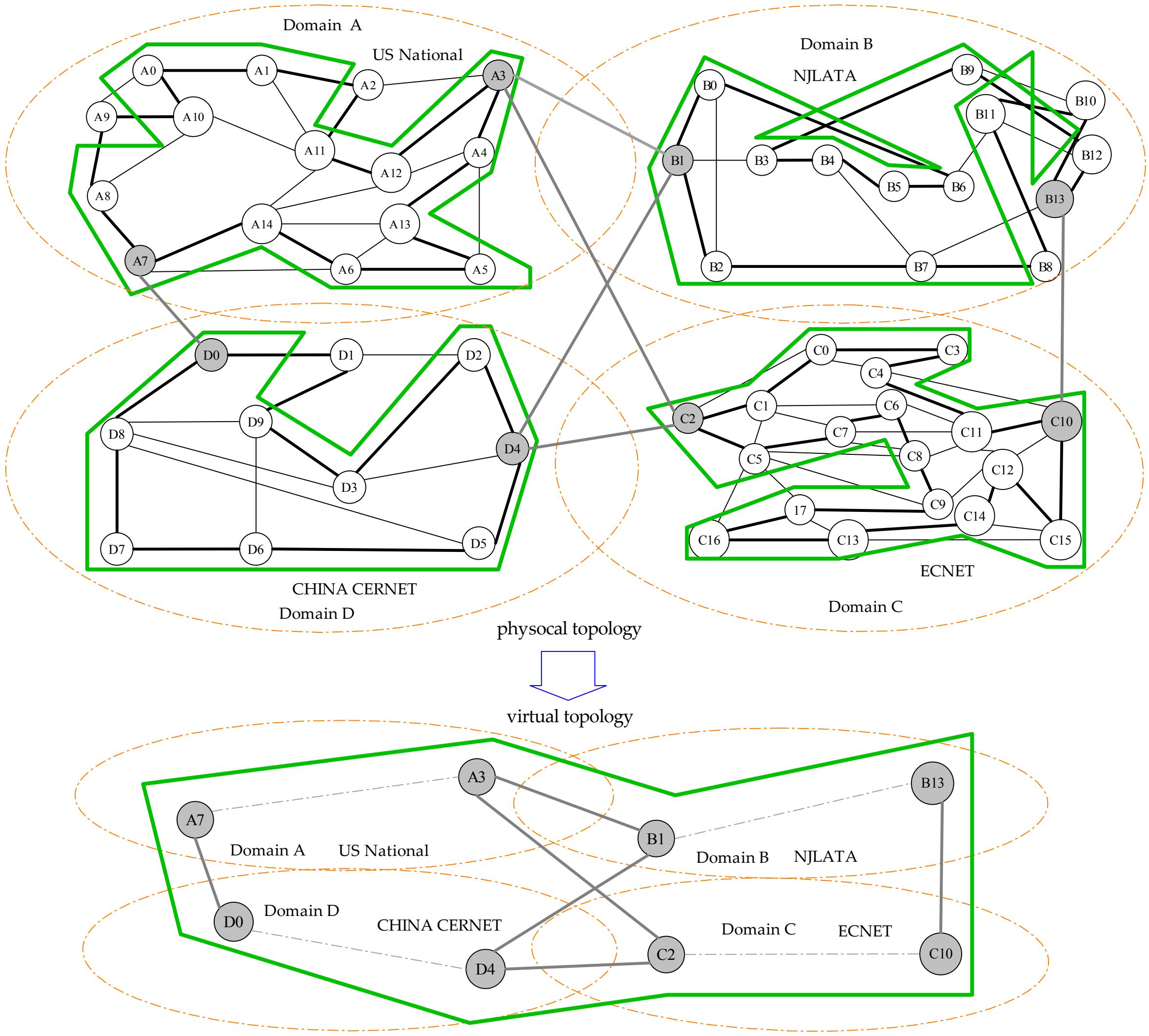
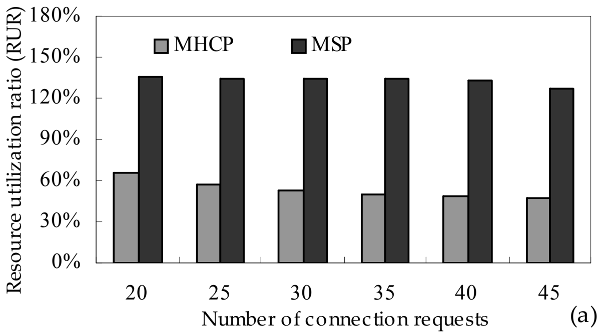


Fig. 2: Test network

4. Simulation and Analysis

The test network is shown in Fig. 2, which includes four domains, where LHC and GHC are shown as thick lines. The granularity of required bandwidth of each connection is one wavelength channel and each fiber link is assumed to have four wavelengths. We simulate an incremental traffic model and evaluate the performances of resource utilization ratio (RUR) and blocking probability (BP) for the proposed MHCP and previous Multi-domain Shared Protection (MSP) algorithm in which the intra-domain protection performs LSSP in [6] and inter-domain protection performs ESPP in [5]. The RUR is defined as the ratio of the total backup wave-lengths over the total working wavelengths, and smaller RUR means better resource utilization ratio. The BP is defined as the ratio of the blocked connection requests over the total connection requests, and smaller BP means higher network throughput.

In Fig. 3 (a), we can see that the resource utilization ratio of MHCP are better than that of MSP, and the improvement ratio of MHCP over MSP is up to 70% which is significant and promising. The reason for this is that, for each single-domain, in Hamiltonian cycle protection all working wavelengths share the common backup wavelengths on Hamiltonian cycle, while in shared-path protection some working wavelengths share some backup wavelengths and other working wavelengths share other backup wavelengths; that is, for each single-domain, the sharability of backup wavelengths in Hamiltonian cycle protection is better than that in shared-path protection, which has been approved by [8]. Since the multi-domains are the combination of multiple single-domains, the result of sharability in single-domain can be extended to multi-domains. Then, compared to MSP that is a case of shared-path protection, the backup wavelengths in MHCP that is a case of Hamiltonian cycle protection are less and the resource utilization ratio in MHCP is better than that in MSP.



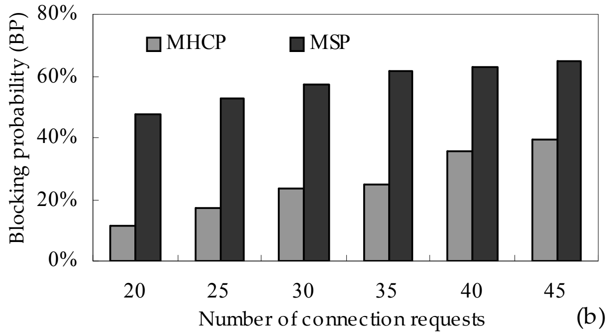


Fig. 3: Simulation results for (a) resource utilization ratio and (b) blocking probability

In Fig. 3 (b), it is shown that the blocking probability of MHCP is lower than that of MSP, and the improvement ratio of MHCP over MSP is up to 40% which is also significant and promising. The reason for this is that MHCP has better resource utilization ratio, and then there will be more free wavelengths can be used by new coming requests. Then, compared to MSP, the blocking probability of MHCP is lower.

5. Conclusion

This paper proposed a new algorithm MHCP to tolerate single-fiber link failure in multi-domain optical networks. MHCP performed LHC based on the physical topology of each single-domain and GHC based on the abstracted virtual topology of multi-domains to protect the intra-link and inter-link failures. Compared to MSP, MHCP can obtain better resource utilization ratio and lower blocking probability.

6. Acknowledgements

This work was supported in part by the National Natural Science Foundation of China (Nos. 60802023, 60673159, 70671020), National High-Tech Research and Development Plan of China (No. 2007AA041201), Key Project of Chinese Ministry of Education (No. 108040), Specialized Research Fund for the Doctoral Program of Higher Education (Nos. 20070145096, 20070145017, 20060145012), Program for New Century Excellent Talents in University, and Hong Kong Polytechnic University Postdoctoral Fellowships Scheme.

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