Hierarchical Logical Topology in WDM Ring Networks with Limited ADMs

Tomoya Kitani[1], Nobuo Funabiki[2],
Hirozumi Yamaguchi[3], and Teruo Higashino[3]

[1] Graduate School of Information Science
Nara Institute of Science and Technology, Nara, Japan
[2] Graduate School of Natural Science and Technology
Okayama University, Okayama, Japan
[3] Graduate School of Information Science and Technology
Osaka University, Osaka, Japan
t-kitani@is.naist.jp, funabiki@cne.okayama-u.ac.jp,
{h-yamagu,higashino}@ist.osaka-u.ac.jp

Abstract. This paper presents a method for constructing logical topology in multi-hop WDM networks hierarchically. Our logical topology can be built over WDM ring networks with only three ADMs (Add-Drop Multiplexers) and transceivers per node. We aim to realize low-cost WDMs that can be deployed for MANs and LANs. Due to well constructed hierarchical topology, both the maximum distance between two nodes and the number of required wavelengths on each optical fiber are reduced to the logarithmic order of the number of nodes. This contributes to mitigate traffic costs in WDM networks. Furthermore, we propose a node labeling scheme to achieve efficient routing without routing table lookup. From our numerical experiments, we have shown that we could construct a logical topology consisting of 1,000 nodes with a very small diameter and 16 wavelengths in a WDM ring network.

Keywords: WDM ring networks, logical topology design algorithm, hierarchical topology, compact routing algorithm

1 Introduction

Wavelength Division Multiplexing (WDM) technology enables high-speed and high-volume data transmission over fiber-optic networks by multiplexing several optical carrier signals using different wavelengths. Because of its significance for very high-speed communication infrastructure, the WDM methodology and the related issues have been widely investigated so far. In particular, since multi-hop WDM networks are required to assign lightpaths among two nodes and any data is carried over those lightpaths, the quality of lightpath design obviously has great impact on the network performance such as the volume of traffic that can be accommodated without causing congestion. Therefore, many algorithms on designing logical topologies over multi-hop WDM networks have been considered [1, 2].

The existing methodologies on logical topology design over WDM networks have focused on minimizing the number of required wavelengths [3–6], the number of required ADMs (Add-Drop Multiplexers) and transceivers [5–7], the blocking probability [8], the number of required paths [9], the total amount of relayed traffic [10, 11], the number of required wavelength converters [3, 12] and so on, for given traffic matrices. It is well-known that the number of ports (ADMs and transceivers) per WDM node has big impact on hardware costs. Also in order to save network resources, minimizing the number of required wavelengths is also desirable. Although some methods try to reduce the total number of ports for cost-efficient design of WDM networks [13], it is desirable to consider WDM networks with a small number of ports per node since MANs and LANs may employ a large number of low-cost nodes. Thus, the traffic grooming methods to minimize the number of ADMs and wavelengths have been investigated so far.

In our previous work [14], we have proposed a logical topology called Hierarchical Chordal Ring Network (HCRN). In HCRN, each node has only three ports (ADMs and transceivers) and the network diameter and the number of required wavelengths are proportional to $\sqrt{N}$ (N denotes the number of nodes). Arora et al. have proposed a method to configure a logical topology for WDM ring networks such as a prevalent MAN [15]. This topology has the network diameter and the number of required wavelengths which are proportional to the logarithmic order of N by using lightpaths with $O(2^N)$ lengths (physical hop-counts). However, this method may require each node to use more ports in the logical topology whereas HCRN uses only three ports.

In this paper, we propose a method of designing a logical topology where the network diameter and the number of required wavelengths are the logarithmic order of N on the WDM ring networks constituted by nodes with only three ports. We also propose a multi-hop routing method over this logical network. This topology is configured by clustering adjacent nodes in a similar way to HCRN and Arora's method. This topology can admit most traffic patterns and variance because of its regularity. Although logical topologies may sometimes be reconfigured according to changes of traffic patterns, frequent reconfiguration cannot be applied in practice due to its overhead. Therefore, it is important to construct a topology which is adaptive to most traffic patterns. Furthermore, exploiting regularity and hierarchy of the logical topology, we propose a node labeling scheme to achieve effective routing on the logical topology without routing table lookup.

From the numerical results, we have shown that we could construct logical topologies of 1,000 nodes with a very small diameter and up to 16 wavelengths per fiber-optic cable, and the method is dominant to the method in Ref. [16] that generates dynamic topologies and Chordal Ring Network topology.

2 Related Work

Reference [16] is one of the initial literatures on logical topology design over optical networks, and provides several heuristic algorithms such as HLDA (Heuristic Logical topology Design Algorithm) and TILDA (Traffic Independent Logical topology Design Algorithm). Later we will conduct performance comparison with them to see efficiency of our method. Reference [6] deals with optical ring networks, and gives the lower bound analysis of wavelengths and ADMs usage in WDM networks. The results indicate to what degree our achievements have been attained; our upper bound analysis shows that we could achieve almost the lowest in most cases. Reference [5] introduces several logical topologies in dynamic lightpath assignment, minimizing the number of transceivers. References [10, 11] also assume SONET ring networks, minimizing the relay traffic on logical topologies by ILP formulation. In particular [10] considers the upper and lower bounds of the minimized relay traffic for cost-efficient design. The recent work [17] has presented the improvement of existing heuristic algorithms by the "rollout" technique.

We have proposed the logical topology called Hierarchical Chordal Ring Network (HCRN) [14]. HCRN is inspired from the Chordal Ring Network topology (CRN) [18], where each node has only three ports (ADMs and transceivers). HCRN achieves less network diameter and less number of required wavelengths than the original CRN by clustering adjacent nodes and configuring internal / inter-cluster lightpaths. However, in both CRN and HCRN, the network diameter and the number of required wavelengths are order of $\sqrt{N}$ (N is the number of nodes). Arora et al. have proposed the method to configure a logical topology for WDM ring networks [15]. The topology achieves that the network diameter and the number of required wavelengths are the logarithmic order of N. In the method, the concept of configuring lightpaths is similar to the distributed hash table (DHT) algorithm named "Chord" for peer-to-peer networks [19]. Both methods use lightpaths/connections whose lengths (physical hop-counts) are power of two. However, they may make each node need more ports in the logical topology whereas it uses only three ports in CRN.

We note that recent researches have dealt with wavelength assignment for high-end, brand-new architectures like WDM networks with wavelength converters [3] and ROADM (Reconfigurable Optical Add-Drop Multiplexer) with modulators [20]. Also some others aim at attaining non-blocking rearrangement [4], achieving fairness in wavelength assignments [12] and so on. Different from those researches, we revisit the important topic; logical path design and routing over WDM networks with limited capabilities of equipments. Even several heuristic solutions have been presented over the last decade, we believe that this problem has not been solved completely and our solution is quite significant for efficient usage of low-cost WDM networks.

3 Target WDM network model

In this section, we show the architecture of WDM networks to explain the problem dealt with in this paper.

An optical network is modeled as a ring graph $G_{phy} = (V, E_{phy})$ where $V = \{0, 1, \cdots, N-1\}$ is a set of nodes and $E_{phy} \subseteq V \times V$ is a set of fiber-optic cables called *physical links* or simply *links*.

Each node is equipped with OADMs (Optical Add-Drop Multiplexers) and for data transmission between two nodes; their transceivers are required to be tuned to a common wavelength in advance. The resulting logical path is called *lightpath*, and the two nodes are called *terminal nodes*. Since each lightpath needs a port (transceiver) at its both terminal nodes, the number of input and output ports at each node is greater than that of lightpaths which are terminated at the node. The number of ports is called *degree bound*.

We show the architecture of WDM nodes in Fig. 1. For a lightpath, each non-terminal node on the lightpath acts as an optical repeater where the optical signal is passed through from an ingress port to the corresponding egress port. Meanwhile, routing is done by the terminal nodes by the conversion between optic signals and electric signals.

We assume the same number of ADMs and transceivers for each node – two ADMs and three transceivers for each node in Fig. 1–, and thus the maximum number of wavelengths on each physical link is identical and is denoted by W. We also assume that in the similar reason, the degree bound of all nodes and the capacity of all the lightpaths are identical, and they are denoted by D and C, respectively.

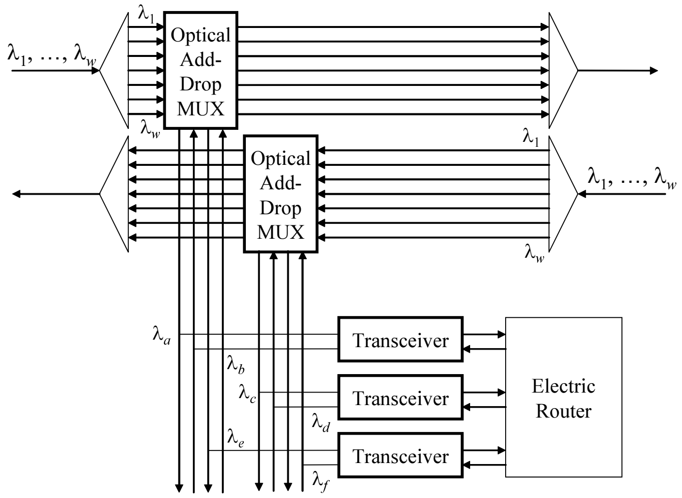


Fig. 1. Architecture of WDM Node

4 Proposed Hierarchical Network Topology

Here, we explain the proposed hierarchical logical topology. We assume a physical ring network $G = (V, E_{phy})$ where $V = \{0, 1, ..., N-1\}$ and $E_{phy} = \{(l, l \oplus 1) | l \in V\}$ is a set of bi-directional physical links ($i \oplus j \equiv (i + j) \bmod N$).

4.1 Clustering of Nodes

In the given physical ring network, a subsequence of nodes in the node ring is called *cluster*. First, we start with a whole, single cluster $[0, ..., N-1]$. As shown in Fig. 2, for each cluster we establish a lightpath called *chord lightpath* between the both end nodes of the cluster, and create two same-sized sub-clusters using the nodes in the cluster except the both end nodes. Then we establish a lightpath between an end node of an i-th level cluster and its physically adjacent node, which is an end node of the $(i+1)$-th level sub-cluster. For each sub-cluster, we repeat the same procedure until the cluster size is less than or equal to four. The consequent hierarchical network topology is called HLT (Hierarchical Logical Topology). As shown in Fig. 3(a), all nodes on this HLT can be clustered hierarchically.

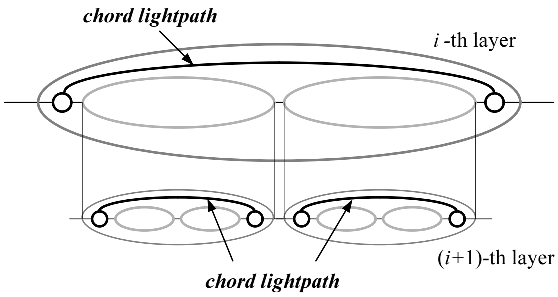
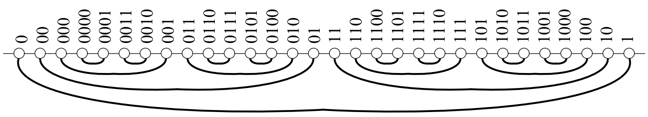
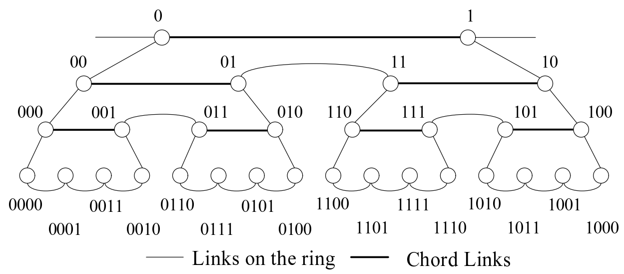


Fig. 2. Clustering of nodes



(a) Hierarchical Construction of "Chords"



(b) Hierarchical Node Labeling

Fig. 3. Node labeling and routing in a cluster of HLT

Then, for routing purpose, we give node labels according to the policy below (see Fig. 3(b)). For the end nodes in the 1st-level (the highest level) cluster, we assign the node labels 0 and 1 to those nodes. If the end nodes of an i-th level cluster have the node labels $X0$ and $X1$, we assign to the end nodes of the $(i+1)$-th level clusters the node labels $X00$, $X01$, $X11$ and $X10$. According to this labeling policy, the nodes in the same level's clusters have the node labels based on Gray codes where the labels of any two nodes that are directly connected by a lightpath differ in only one digit (Fig. 3). Also if a node p of $(i+1)$-th level cluster is connected by a lightpath with a node of i-th level cluster with node label Y, the node label of p is $Y0$. These codes are called *variable length Gray codes*.

In this hierarchical logical topology HLT, the network diameter (the maximum distance (hop count) between two nodes in the network) is $O(\log N)$. One may think that this is similar with the Chordal ring network topology [18], however its network diameter is $O(\sqrt{N})$. Thus, the proposed hierarchical topology HLT can attain smaller network diameters than Chordal Ring Network topology in large-scale networks.

As shown in Fig. 3, all the chord lightpaths established in the clusters of the same level can use a common wavelength because they never share the physical links. Therefore, as a total, we only need H wavelengths where H is the number of hierarchy levels. Since $N \leq 2^{H+1} - 2$, the number of required wavelengths is obtained as follows;

$$H = \lceil \log_2 (N+2) \rceil - 1 \simeq \log_2 N \qquad (1)$$

We note that if we use a physical ring network topology, the wavelength for the 1st level can be the same as that used for the second level, and this can save one wavelength. For example, in Fig. 3, the wavelength assigned to the chord lightpath between nodes 0 and 1 can be the same as that used for the two chord lightpaths between 00 and 01 and between 11 and 10 since there is a direct physical link between nodes 0 and 1. As we have seen above, the most significant feature of HLT is that the network diameter and the number of required wavelengths are suppressed to the logarithmic order of N.

4.2 Routing on Proposed Hierarchical Logical Topology

Here, we consider a routing on the proposed network topology.

For routing on the hierarchical topology HLT, as shown in Fig. 3(b), the proposed variable length Gray codes can be used for deciding the route from a source node to its destination node. If nodes 001 and 1001 are the source node and its destination node respectively, the path 001, 000, 00, 0, 1, 10, 100, 1000, 1001 is one of the shortest routes. Basically, each packet is relayed from the source node to a node on an upper level, and then it is forwarded from the node on the upper level to the destination node. This is the basic routing policy. There is an exception. If nodes 00 and 111 are the source node and its destination node, the path 00, 01, 11, 110, 111 is the shortest route, and the route through 00, 0, 1, 10 becomes longer. The lightpath from 01 to 11 makes the length of the route shorter. For each node S with node label $s_1, s_2, \cdots, s_k$, there are four routing actions. UP denotes the action which forwards the received packet to its parent node $S_{UP} = s_1, s_2, \cdots, s_{k-1}$. UP can be used only for $s_k = 0$. DW denotes the action which forwards the received packet to its child node $S_{DW} = s_1, s_2, \cdots, s_k, 0$ ($s_{k+1} = 0$). BR denotes the action which forwards the received packet to its sibling node $S_{BR} = s_1, s_2, \cdots, s_k \oplus 1$ through the chord lightpath (or normal lightpath) between $s_1, s_2, \cdots, s_k$ and $s_1, s_2, \cdots, s_k \oplus 1$. Here, note that $x \oplus 1 = 1$ if $x = 0$, and that $x \oplus 1 = 0$ if $x = 1$. CO denotes the action which forwards the received packet to its cousin node $S_{CO} = s_1, s_2, \cdots, s_{k-1} \oplus 1, s_k$ through the lightpath between $s_1, s_2, \cdots, s_k$ and $s_1, s_2, \cdots, s_{k-1} \oplus 1, s_k$. CO can be used only for $s_k = 1$. Hereafter, Forward(S, UP), Forward(S, DW), Forward(S, BR) and Forward(S, CO) denote the forwarded nodes S_{UP}, S_{DW}, S_{BR} and S_{CO}, respectively.

Let $S = (s_1, \cdots, s_i, s_{i+1}, \cdots, s_k)$ and $D = (s_1, \cdots, s_i, d_{i+1}, \cdots, d_h)$ denote the variable length Gray codes for nodes S and D. Here, we assume that the first i bits of the variable length Gray codes of nodes S and D are the same ($s_{i+1} \neq d_{i+1}$). The following algorithm **R-HLT**(S,D) calculates the routing action of node S (here, "NIL" denotes no action).

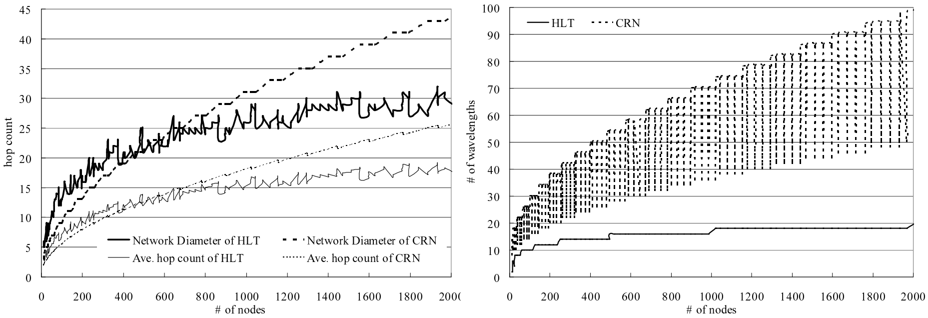
[**Routing Algorithm R-HLT**]:
if ($S = D$) **then** "NIL"
else
  if ($(k - i > 2) \vee (h = i)$) **then**
    if ($s_k = 0$) **then** "UP" **else** "BR"
  else if ($k - i = 2$) **then**
    case (s_{k-1}, s_k) **of**
      $(0, 0)$: **if** ($k > h$) **then** "UP" **else** "BR"
      $(0, 1)$: **if** ($d_{k-1} = 0$) **then** "BR" **else** "CO"
      $(1, 0)$: **if** ($d_{k-1} = 0$) **then** "CO" **else** "BR"
      $(1, 1)$: **if** ($k > h$) **then** "UP" **else** "BR"
    end
  else if ($k - i = 1$) **then** "BR"
  else (* $k = i$ *) "DW"

If node S is a source node or relay node, the above routing algorithm **R-HLT**(S,D) can decide the routing action of node S when S must forward its received packets to node D. If the source node S wants to decide the strict routing path and its length from node S to its destination node D, we can calculates them by repeating **R-HLT** and calculating the path $S_0 = S$, $S_1 =$Forward(S,**R-HLT**(S, D)), $S_2 =$Forward(S_1,**R-HLT**(S_1, D)), $\cdots$, $S_q = D =$Forward(S_{q-1},**R-HLT**(S_{q-1}, D)) until we find node D as S_q. This path denotes the strict routing path from S to D and its path length is q. This routing can be used when we use source routing.

5 Performance Evaluation and Numerical Results

5.1 Comparative Models

Here, we will explain existing logical topologies which can be applied for WDM networks with node degree 3. A Chordal ring network has a ring topology with N nodes (N must be even) whose node IDs are 0 to $N - 1$. For each node with node ID k, one chord is connected to either node $k + L$ or $k - L$. Here, L denotes a constant number. In Ref. [18], it is shown that if $\sqrt{N} + 3 \leq \frac{N}{2}$ holds, we can maximize its network diameter when an odd number closest to $\sqrt{N} + 3$ is specified as the constant L. If $\sqrt{N} + 3 \leq \frac{N}{2}$



(a) Network diameter and average hop count   (b) Number of required wavelengths

Fig. 4. Comparison between HLT and CRN

does not hold, we can assign the maximum odd number which is less than or equal to $\frac{N}{2}$ as the constant L. In this situation, the network diameter and the number of required wavelengths of CRN are both proportional to the square root of the number N of nodes. On the other hand, as we explained above, the proposed HLT topology only requires the network diameter and the number of required wavelengths which are proportional to the logarithmic order of N. Figure 4 denotes the comparison about the network diameter, the average hop counts and the number of required wavelengths of HLT and CRN networks. Note that, as shown in Fig. 4(b), CRN needs twice the number of wavelengths in order to construct itself when N cannot be divided by the chord length L.

There are also some dynamic topology construction methods. For example, in Ref. [16], HLDA (Heuristic Logical topology Design Algorithm) and TILDA (Traffic Independent Logical topology Design Algorithm) are proposed, and they are often used for performance comparison.

In HLDA, in order to minimize the total amount of traffic, nodes with heavy traffic are given priority to use usable optical wavelengths. In HLDA, the following algorithm is used.

Algorithm HLDA

Step.0 An optical link is given between every physically adjacent nodes so that all nodes can communicate each other.

Step.1 Estimate the traffic amount P_{ij} for every link (i, j).

Step.2 Find link (i, j) whose P_{ij} is maximum. If there is an usable wavelength on the link (i, j), we assign one wavelength to link (i, j). Then, we set P_{ij} to 0.

Step.3 If all P_{ij} are 0, go to Step.4. Otherwise, return to Step.2.

Step.4 If we still have usable wavelengths, we assign those wavelengths to possible links randomly. We repeat this process until we cannot assign new wavelengths.

On the other hand, TILDA does not consider traffic amounts, and gives priority for assigning usable wavelengths to physically closer links. In TILDA, the following algorithm is used.

Algorithm TILDA

Step.0 An optical link is given between every physically adjacent nodes so that all nodes can communicate each other.

Step.1 Set $i = 2$.

Step.2 If a node has usable ADMs and if there is a usable wavelength on the path from the node to another node with i hop distance, we assign one wavelength to all links on the path. If there is no such a path for two nodes with i hop distance, we set $i = i + 1$ and repeat the same process.

5.2 Performance Evaluation

We have evaluated the performance of the proposed HLT, HLDA and TILDA by simulation. Here, we have used three types of traffic matrices: random model, server-client model and small-world model. In our analyses, we have changed the number N of nodes from 50 to $1,000$ in units of 50 nodes, and tried three numerical analyses for the above three types of traffic matrices, respectively. Here, we assume that HLDA can also use the same number of wavelengths as much as that used in the proposed method. The uniform random numbers between 0 and 1 are given as the traffic matrix of the random model. In the server-client model, 5% of nodes are selected as servers, and we have sent 10 times of traffic to those server nodes. In the small-world model, first we construct a traffic matrix based on the server-client model, and then we make traffic among neighboring nodes increase 10 times [21]. We also make the traffic between two nodes decrease in proportion to the distance between two nodes.

For the given traffic matrices, we have evaluated the network diameters, the average number of hops, and overall traffic volume. The traffic volume, denoted by Q hereafter, is defined as follows;

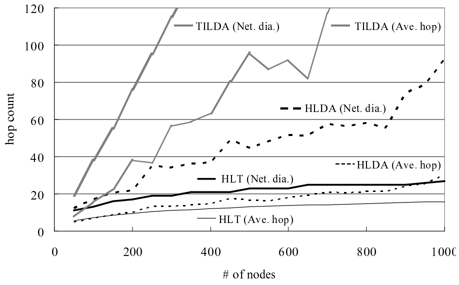
$$Q = \sum_u \sum_v T^{uv} \cdot h^{uv} \tag{2}$$

where h^{uv} and T^{uv} denote the number of lightpaths and traffic on the route from u to v, respectively.

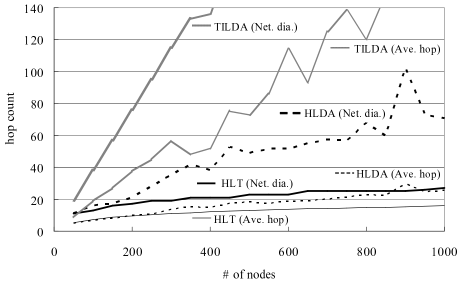
We show our numerical results for the above three models in Fig. 5. Figure 5(a)–(c) denotes the network diameters and average numbers of hop counts. Figure 5(d) denotes the overall traffic volumes Q where all the traffic volumes are normalized so that the traffic volume of HLDA is represented as 1.

For all the traffic models, if the number of nodes exceeds 100, the proposed logical topology HLT is better than other topologies. The reason is that if the number of nodes is small, relatively we can use more wavelengths. On the other hand, if the number of nodes becomes large, relatively we can use less wavelengths. If HLDA can assign enough number of logical links between nodes with heavy traffic, we can assign enough number of logical links. However, if the number of nodes becomes large, we might not be able to assign enough number of logical links for such purposes.

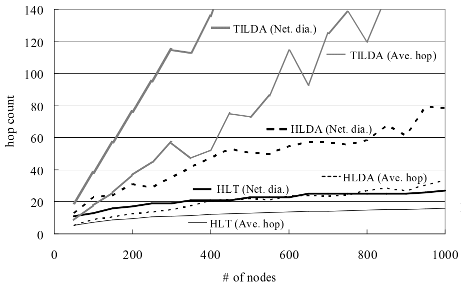
For the network diameters, in the proposed hierarchical topology HLT, the network diameters are stable independently of traffic fluctuation and deviation. On the other hand, HLDA gives priority to assigns logical links for node pairs with heavy traffic. This makes the hop counts for node pairs with light traffic increase. The traffic fluctuation and deviation also make big influence to the network diameters.



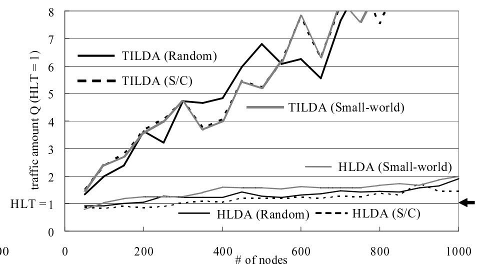
(a) Net. dia. and ave. hop counts
on Random model



(b) Net. dia. and ave. hop counts
on Server-Client model



(c) Net. dia. and ave. hop counts
"Small-world" model



(d) Ratio of network traffic amounts
in HLT, HLDA and TILDA (HLT = 1)

Fig. 5. Network diameter, average hop counts and traffic amounts in HLT, HLDA and TILDA

Next, we focus on the average hop counts and total traffic volumes for the random model and server-client model. In HLDA, the average hop counts are small for the random model since optical fiber links are assigned uniformly. In the server-client model, the total traffic volumes relatively become small since HLDA gives priority to assign logical links for node pairs with heavy traffic. Since the proposed topology is regular, it offers almost fixed performance independently of traffic models and volumes. It can also guarantee the upper limit of the network diameters theoretically. In general, the random model and server-client model have similar tendency for the average hop counts.

Lastly, we focus on the average hop counts and total traffic volumes for the small-world model. HLDA assigns many optical links for neighboring node pairs since we assume relatively heavy traffic to neighboring node pairs. Then, it becomes difficult to assign optical links for node pairs with long distances. On the other hand, the proposed topology can assign hierarchical chords for node pairs with long distances while neighboring node pair can communicate with each other using the links on the original ring topology. From the above reason, our proposed topology HLT and HLDA have rather different tendency. In Fig. 5(d), if the number of nodes is more than 400, the total traffic volumes of the proposed topology HLT is less than 60% of those for HLDA.

We can observe that our topology could save the usage of wavelengths because it could uniformly distribute lightpaths over physical links. As shown in Fig. 5(d), for a logical topology with 1,000 nodes, an HLT topology only requires 16 wavelengths. Meanwhile, in HLDA and TILDA, it is likely to occur that some lightpaths are established over some specific physical links first due to degree limitations. In that case no more lightpaths were accepted over the link if no more wavelength is available, and the other lightpaths are needed to detour the link. Thus consequent topologies may have long routes that require many hops and make the diameters larger.

6 Conclusion

In this paper, we propose a design method of hierarchical logical topology in multi-hop WDM networks. Our logical topology can be built over WDM networks with limited ADMs. The method can be applied for both ring-type and mesh-type WDM networks. The proposed logical topology has features that both the maximum distance between two nodes and the required number of wavelengths on each physical optical link are proportional to the logarithmic order of the number N of nodes. From theoretical and numerical points of views, we have compared the proposed logical topology with general Chordal ring network topology and HLDA (Heuristic Logical topology Design Algorithm) based network topology. The proposed logical topology has smaller average hop number, network diameter and total traffic amount. If the number N of nodes on a given WDM network becomes large, our logical topology becomes more efficient. It is shown that the proposed logical topology has enough scalability for large scale WDM networks. We have also shown that the network performance can be further improved by combining HLDA over our logical topology.

To investigate detailed network performance on real WDM networks is one of our future work.

References

1. R. Dutta and G.N. Rouskas: “A survey of virtual topology design algorithms for wavelength routed optical networks,” *Optical Network Magazine*, vol. 1, pp. 73–89 (2000).
2. H. Zang, J.P. Jue and B. Mukherjee: “A Review of Routing and Wavelength Assignment Approaches for Wavelength-Routed Optical WDM Networks,” *Optical Networks Magazine*, vol. 1, no. 1, pp. 47–60 (2000).
3. L-W. Chen and E. Modiano: “Efficient Routing and Wavelength Assignment for Reconfigurable WDM Ring Networks With Wavelength Converters,” *IEEE/ACM Trans. on Networking*, vol. 13, no. 1, pp. 173–186 (2005).
4. P. Saengudomlert, E.H. Modiano and R.G. Gallager: “Dynamic Wavelength Assignment for WDM All-Optical Tree Networks,” *IEEE/ACM Trans. on Networking*, vol. 13, no. 4, pp. 895–905 (2005).
5. O. Gerstel, R. Ramswami and G.H. Sasaki: “Cost-Effective Traffic Grooming in WDM Rings,” *IEEE/ACM Trans. on Networking*, vol. 8, no. 5, pp. 618–630, (2000).
6. A.R.B. Billah, B. Wang and A.A.S Awwal: “Effective Traffic Grooming in WDM Rings,” *Proc. of the 45th IEEE Global Telecomm. Conf.(GLOBECOM 2005)*, vol. 3, pp. 2726–2730 (2002).

7. S. Janardhanan, A. Mahanti, D. Saha and S.K. Sadhukhan: “A Routing and Wavelength Assignment (RWA) Technique to Minimize the Number of SONET ADMs in WDM Rings,” *Proc. of the 39th Annual Hawaii Int’l Conf. on Sys. Sci. (HICSS ’06)*, vol. 2 (2006).
8. C. Liu and L. Ruan: “Logical Topology Augmentation for Survivable Mapping in IP-over-WDM Networks,” *Proc. of the 48th IEEE Global Telecomm. Conf.(GLOBECOM 2005)*, vol. 4 (2005).
9. C. Xin, B. Wang, X. Cao and J. Li: “A Heuristic Logical Topology Design Algorithm for Multi-Hop Dynamic Traffic Grooming in WDM Optical Networks,” *Proc. of the 48th IEEE Global Telecomm. Conf.(GLOBECOM 2005)*, vol. 4 (2005).
10. K. Lee and K-Y. Siu: “On the Reconfigurability of Single-Hub WDM Ring Networks,” *IEEE/ACM Trans. on Networking*, vol. 11, no. 2, pp. 273–284 (2003).
11. R. Dutta and G.N. Rouskas: “On Optimal Traffic Grooming in WDM Rings,” *IEEE J. on Select. Areas in Commun.*, vol. 20, no. 1, pp. 110–121 (2002).
12. K. Mosharaf, I. Lambadaris, J. Talim and A. Shokrani: “Fairness Control in Wavelength-Routed WDM Ring Networks,” *Proc. of the 48th IEEE Global Telecomm. Conf.(GLOBECOM 2005)*, vol. 4 (2005).
13. B. Schein and E. Modiano: “Quantifying the Benefit of Configurability in Circuit-Switched WDM Ring Networks with Limited Ports per Node,” *J. of Lightwave Tech.*, vol. 19, no. 6, pp. 821–829 (2001).
14. T. Kitani, N. Funabiki and T. Higashino: “Proposal of Hierarchical Chordal Ring Network Topology for WDM Networks,” *Proc. of the IEEE Int’l Conf. on Networks 2004 (ICON2004)*, pp. 605–609 (2004).
15. A.S. Arora, S. Subramaniam and H-A. Choi: “Logical Topology Design for Linear and Ring Optical Networks,” *IEEE J. on Select. Areas in Commun.*, vol. 20, no. 1, pp. 62–74 (2002).
16. R. Ramaswami and K.N. Sivarajan: “Design of logical topologies for wavelength-routed all-optical networks,” *Proc. of the 14th IEEE Int’l Conf. on Comp. Comm. (INFOCOM ’95)*, pp.1316–1325 (1995).
17. K. Lee and M.A. Shayman: “Rollout Algorithms for Logical Topology Design and Traffic Grooming in Multihop WDM Networks,” *Proc. of the 48th IEEE Global Telecomm. Conf.(GLOBECOM 2005)*, vol. 4 (2005).
18. B.W. Arden and H. Lee: “Analysis of Chordal Ring Network,” *IEEE Trans. on Comp.*, C-30, no.4, pp.291–295 (1981).
19. I. Stoica, R. Morris, D. Liben-Nowell, D.R. Karger, M.F. Kaashoek, F. Dabek and H. Balakrishnan: “Chord: a scalable peer-to-peer lookup protocol for Internet applications,” *IEEE/ACM Trans. on Networking*, vol. 11, no. 1, pp. 17–32 (2003).
20. O. Turkcu and S. Subramaniam: “Blocking in Reconfigurable Optical Networks,” *Proc. of the 26th IEEE Int’l Conf. on Comp. Comm. (INFOCOM 2007)*, pp. 188–196 (2007).
21. D.J. Watts and S.H. Strogatz: “Collective dynamics of ‘small world’ networks,” *Nature*, vol.393, pp.440–442 (1998).