

Design Methodology for WDM Backbone Networks using Traffic-Aware Heuristic Algorithm

Aneek Adhya⁺, Partha Goswami^{*}, Soumya K. Ghosh,^{*} and Debasish Datta⁺

⁺ Dept. of Electronics & ECE, IIT Kharagpur

^{*} School of Information Technology, IIT Kharagpur

E-Mail : {aneek@ece, parthag@sit, skg@sit, ddata@ece}.iitkgp.ernet.in

Abstract– The problem of logical topology design and traffic routing over the lightpaths for wavelength-routed optical networks has been investigated extensively in the past using heuristic as well as linear-programming based approaches. However, these methodologies are in general carried out for a given traffic matrix and their performance depends on the nature of traffic distribution amongst node pairs. Thus, these methodologies may not perform equally well for networks with uniform and nonuniform (clustered) traffic distributions. In the present work, we present a novel design methodology that addresses this aspect of network traffic, leading to a traffic-aware design that offers better performance as compared to the existing techniques.

I. Introduction

Wavelength-routed optical network using wavelength-division multiplexing (WDM) is considered to be potential candidate for next-generation backbone networks [1], [2], [3]. Such networks consist of optical cross-connects (OXC) interconnected by optical fibres. Electronic devices like IP routers, ATM switches, SONET terminals remain connected to these OXCs. While wavelength routing reduces electronic processing cost, optical-electrical-optical (O/E/O) conversion at OXCs enables more traffic to be groomed. Though setting up direct lightpaths among all source-destination pairs is generally the best solution, it might not be feasible due to limited resources and physical constraints. As a consequence, designing logical topology and routing of traffic through those logical paths can be formulated as an optimization problem; performance metric for such design may be chosen as congestion, delay, average hop-count, blocking probability, throughput, traffic scale-up or some appropriate combination of them. Since this optimization problem using linear programming (LP) is often computationally intractable for larger networks, it is usually convenient to split the task in two subproblems: logical topology design (LTD) by choosing a set of direct (i.e., single-hop) lightpaths between a set of specific candidate node pairs and routing and wavelength assignment (RWA) of these lightpaths¹, followed by the

routing of network traffic over the lightpaths designed in the first phase [4], [5], [6]. Solutions (lightpaths embedded over specific physical links, nodes and wavelengths) from first subproblem are supplied to the second subproblem to obtain a near-optimal result.

As mentioned in the above, the heuristic-based approaches for LTD offer more-easily realizable solutions as compared to the LP-based design optimization. In view of this, in the present work, we explore further on possible heuristic approaches towards finding more efficient design methodologies. It may be noted that, the earlier methods on LTD [5] did not address the dependence of the LTD performance (e.g., congestion or delay) on the nature of traffic matrix of the network under consideration. In general, the traffic between source-destination (SD) pairs in a network may not be uniformly distributed, thereby making a few SD pairs demanding more bandwidth as compared to the others. Thus, all the SD pairs in the network may be divided into at least two (or more) clusters depending on their bandwidth demands. It appears from the results reported in the literature that, the existing heuristic approaches may not perform equally well for uniform and non-uniform (clustered) traffic distribution in a given network. In the present work, we attempt to design a methodology that addresses this aspect of network traffic and eventually offers a traffic-aware heuristic algorithm.

In order to design a traffic-aware design methodology, we adapt the heuristic algorithms used in [5] viz., heuristic logical topology design algorithm (HLDA) and random logical topology design algorithm (RLDA) for the first subproblem and apply appropriate combinations of HLDA and a modified version of RLDA to different clusters of SD pairs, leading to a traffic-aware hybrid logical topology design algorithm (TA-HTDA). Having designed the logical topology using TA-HTDA, the traffic-routing sub problem is performed using a propagation-delay-constrained heuristic approach, instead of using LP-based solution used in [5]. Eventually we show that the proposed method offers better solutions (i.e., lesser congestion with more stringent delay constraint) both in case of clustered and uniform traffic distributions. Rest of the paper is organized as follows.

In Section II we present the details of the proposed LTD algorithm followed by the propagation-delay-constrained

¹ Hereafter, for the sake of brevity, we refer this subproblem as LTD only

traffic distribution algorithm. We have used HLDA, RLDA and TA-HTDA for 14-node NSFNET [5] using two different sets of traffic matrix. Results and discussion on the performance of the proposed method are presented in Section III. Finally, in Section IV, we present the concluding remarks on the work.

II. Traffic-Aware Hybrid Design Methodology

Before we describe the proposed design methodology (TA-HTDA), it may be worthwhile to describe the existing algorithms, viz., HLDA and RLDA that are eventually employed judiciously in TA-HTDA. In HLDA the algorithm starts with a given physical topology, traffic matrix, maximum number of permissible wavelengths in a physical link and a nodal degree (maximum allowable number of transmitters/receivers which is assumed to be same for all nodes). In general, SD pairs with significant traffic-demand are given higher priority. To begin with, the highest element in the given traffic matrix is selected; a direct lightpath is constructed in shortest possible path (minimum propagation delay) between the SD pair subject to the availability of transceivers and wavelengths in the candidate physical route-links. On successful completion of this step, free transceivers at each source/destination node and permissible free wavelengths in each physical link are updated. Thereafter, the second highest element in traffic matrix is subtracted from the highest element and the remaining traffic is retained to indicate (in the later phase of the algorithm) the significance that this highest element of the matrix might be favoured with another direct lightpath, provided this residual traffic exceeds the existing/remaining traffic elements at any stage during the execution of the algorithm. Highest traffic element is reduced to zero if no common free wavelength is available in all physical links constituting shortest path or transceivers at SD pair are not free. Thereafter the next highest element is picked up and the same process is repeated, and this process is continued until entire traffic matrix becomes zero. If the entire traffic matrix reduces to zero in this process and some of the transceivers yet remain unused, a SD pair is selected on random basis for establishment of lightpath and the shortest path is attempted to route the lightpath satisfying the nodal degree (transceivers) and wavelength constraints. This becomes an iterative approach, which is continued until all transceivers are exhausted or no path becomes feasible. In RLDA, logical edges are placed entirely at random, subject to finding a lightpath for each edge and not violating degree constraints, but ignoring the traffic matrix.

Since in RLDA a direct lightpath between a SD pair is selected in random manner, more than one lightpath between two nodes can't be refused even if the traffic is not significant. Presence of more than one lightpath between two nodes with small traffic strength may become counter-productive for

congestion control as it enhances multihop traffic instead of single hop traffic for other SD pairs. To alleviate this problem we first propose a modified version of RLDA, referred to as recursive RLDA (RRLDA). Thereafter, we present the proposed design methodology in the following subsections.

A. RRLDA

In RRLDA, our objective is to construct lightpaths between SD pairs in a random yet judicious manner. In this scheme, in the first phase we try to set up lightpaths among distinct SD pairs selected randomly, i.e., more than one lightpath between the same SD pair is denied initially. However, in the subsequent phase (i.e., after executing the first phase of the algorithm), if there remains unused transceivers and wavelengths the algorithm revisits the already-assigned SD pairs to assign more lightpaths, again following a random manner. To implement this policy we define two arrays **Forbidden** and **Connection-not-possible** (each of size N^2 , N is total number of nodes in network) wherein in the initialization phase the *Number* ($s*N+d$) for $s=d$ and $s, d = 0,1,\dots,N-1$ (i.e., the diagonal elements of traffic matrix) are only included and remaining elements (N^2-N) are initialized with a unique number (beyond $[0, N^2-1]$ range – we use a negative number, say -5). Subsequently, we randomly generate a number within $[0, N^2-1]$ range and not already included in **Forbidden** array for identifying the SD pair where, $s=Number/N$ and $d=Number \bmod N$ in order to construct lightpath between that SD pair and replace the first negative element in **Forbidden** by the *Number*. While constructing the lightpath we check the feasibility based on the physical (availability of wavelengths) and resource (availability of transceivers) constraints. All those *Numbers* corresponding to SD pairs through which lightpaths could not be established are included in the **Connection-not-possible** array by replacing first negative number. This process, excluding the initialization step is continued until **Forbidden** array contains no negative element. In second phase onwards, we initialize only **Forbidden** array and repeat the same process until **Connection-not-possible** array is filled with nonnegative elements (i.e., when design constraints limits further lightpath allocation).

As described in the above, RRLDA is a modified version of RLDA [5] wherein lightpaths are assigned between SD pairs more judiciously. In order to develop more efficient logical topology sensitive to traffic patterns, we propose a traffic-aware hybrid method combining the benefits of both HLDA and RRLDA.

B. Traffic Clustering and TA-HTDA

In a backbone network, the busy metros would have higher incoming and outgoing traffic than other locations. In view of this, as mentioned in Section I, we divide all the SD pairs in a

given network into two clusters: one with higher traffic demands (for bandwidth) and the other with relatively lower traffic demands. Subsequently, we apply different LTD schemes for the two clusters. In particular, we employ HLDA for the cluster with higher traffic demands, while for the remaining cluster RRLDA is used. It is expected that HLDA suit the higher-demand cluster with its preference to allow lightpaths for high-traffic SD pairs, while RRLDA can assign lightpaths suiting the needs of the remaining SD pairs. In view of the above, we therefore need an appropriate clustering scheme to divide the SD pairs of a given network into two clusters. We describe the clustering scheme in the following.

Let $T(s,d)$ represent the traffic demand between a source node s and a destination node d . The proposed clustering technique will divide the traffic demand matrix $T=\{T(s,d)\}$ into two matrices, namely high-demand traffic matrix T_{HI} and low-demand traffic matrix T_{LO} . In T_{HI} , all the large traffic demands are retained, while lower demand elements are replaced by zero. Similarly in T_{LO} all the low traffic demands are retained, while the higher demand elements are replaced by zero, so that $T = T_{HI} + T_{LO}$. The steps followed in generating T_{HI} and T_{LO} are as follows.

- Step 1:* Copy the traffic matrix T to temporary traffic Matrix Q
- Step 2:* Initialize $T_{HI} = 0$ and $T_{LO} = 0$
- Step 3:* Identify the highest element of Q , $Q(s_{Max}, d_{Max})$
- Step 4:* $T_{HI}(s_{Max}, d_{Max}) = Q(s_{Max}, d_{Max})$
- Step 5:* $Q(s_{Max}, d_{Max}) = -1$
- Step 6:* Identify the lowest non-negative element of Q , $Q(s_{Min}, d_{Min})$
- Step 7:* $T_{LO}(s_{Min}, d_{Min}) = Q(s_{Min}, d_{Min})$
- Step 8:* $Q(s_{Min}, d_{Min}) = -1$
- Step 9:* Compute the centroid C_{HI} , average value of the traffic elements in high-demand traffic cluster.
- Step 10:* Compute the centroid C_{LO} , average value of the traffic elements in low-demand traffic cluster.
- Step 11:* for all elements of Q , while $Q(s,d) > 0$
- a. Identify the highest element of Q , $Q(s_{Max}, d_{Max})$
 - b. $Max_element = Q(s_{Max}, d_{Max})$
 - c. $Q(s_{Max}, d_{Max}) = -1$
 - d. if $((C_{HI} - Max_element)^2 \leq (Max_element - C_{LO})^2)$
 - i. $T_{HI}(s_{Max}, d_{Max}) = Max_element$
 - ii. Compute the centroid C_{HI} .
- Else
- i. $T_{LO}(s_{Max}, d_{Max}) = Max_element$
 - ii. Compute the centroid C_{LO}
- Step 12:* End

It may be noted that T_{HI} and T_{LO} are passed on as inputs to the TA-HTDA scheme along with the adjacency matrix of the physical topology. A description of the major steps in TA-HTDA is presented in the following.

- Step1:* Design logical topology using HLDA for traffic matrix T_{HI} while the highest element of T_{HI} remains greater than highest element of T_{LO} .
- Step 2:* Update total number of free transmitters and receivers present in each node.
- Step3:* Update set of unused wavelength available in each physical link.
- Step 4:* Design logical topology using RRLDA for traffic matrix T_{LO} .
- Step 5:* Construct a single resultant logical topology

This completes the first subproblem with lightpaths designed and routed with appropriate wavelengths for the given physical network. Using the results of TA-HTDA, we construct the lightpath delay matrix LPD containing lightpath propagation delays between node pairs if lightpaths exist and the lightpath count matrix LPC containing the number of lightpaths existing between a node pair. These two matrices are passed on to the next phase as inputs.

C. Traffic Routing Scheme

In this section, we consider the traffic-routing subproblem over the logical topology designed using HLDA, RLDA and TA-HTDA. The traffic routing subproblem is concerned with traffic routing between the SD pairs over the logical topology. If two nodes are connected by an edge in a logical topology, traffic can be transmitted from one node to another without any O/E/O conversion at intermediate nodes. However, otherwise the traffic may also flow over multiple lightpaths concatenated via intermediate nodes (multi-hop connection) using O/E/O conversion. With a given traffic demand of an SD pair, one can also utilize, if necessary, more than one such single-hop/multi-hop routes, while satisfying some preassigned constraint on the minimum acceptable propagation delay (information on propagation delay being provided by the LPD matrix).

Each of the N nodes (or the specific co-ordinating node(s), depending on whether centralized or distributed control is employed for the purpose) in the network are assumed to be aware of the traffic matrix $T_{N \times N}$ and the logical topology G_L in terms of LPD and LPC matrices. The traffic flow f_{ij} in the logical link from node i to node j of the G_L consists of traffic from different pairs of source (s) and destination (d) nodes. The traffic originated from the (s, d) pair and flowing through i - j logical link is represented as $f_{ij}^{s,d}$. Therefore, one can express f_{ij} as

$$f_{ij} = \sum_{s,d} f_{ij}^{s,d} \quad (1)$$

The congestion C_{ij} in each of the lightpaths between i - j nodes can be expressed as

$$C_{ij} = f_{ij} / LPC(i,j) \quad (2)$$

where, $LPC(i,j)$ is the number of lightpaths between the i - j nodes. Propagation delay of the logical link i, j is defined as

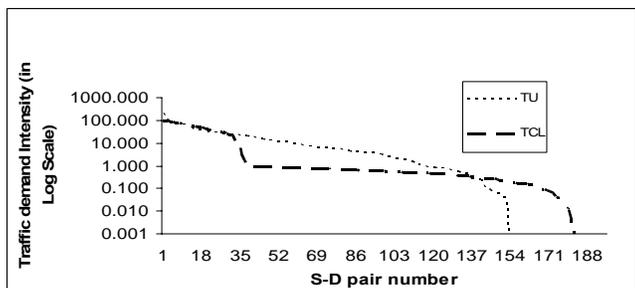


Fig 2: Traffic Demands in descending order for traffic matrices T_U and T_{CL} .

α	Congestion (TA-HTDA+ traffic routing heuristic)	Congestion (HLDA + traffic routing heuristic)	Congestion (RLDA+ Traffic routing heuristic)
2	116.37	Infeasible	Infeasible
3	83.30	151.64	135.73
4	79.97	134.51	174.52
9	74.64	117.06	168.9

Table 1: Congestion benefit using TA-HTDA for T_{CL} with nodal degree =3.

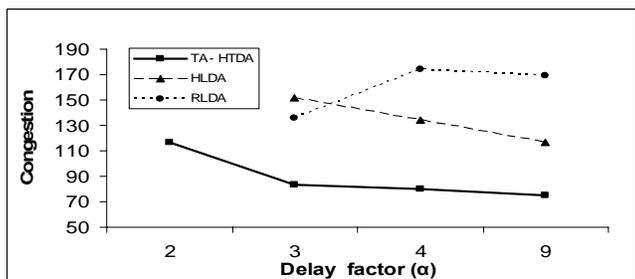


Fig 3: Congestion for nonuniform (clustered) traffic Matrix T_{CL} .

α	Congestion (HTDA+ traffic routing heuristic)	Congestion (HLDA + traffic routing heuristic)	Congestion (RLDA+ Traffic routing heuristic)
3	168.12	200.57	162.75
4	135.42	182.301	147.64
5	138.69	167.82	145.71
10	136.05	170.10	152.3

Table 2: Congestion benefit using TA-HTDA for T_U with nodal degree =3.

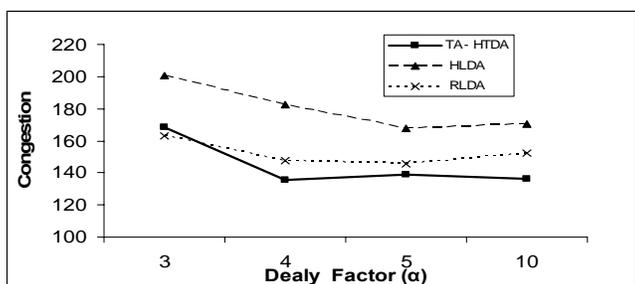


Fig 4: Congestion for uniformly distributed traffic Matrix T_U

IV. Conclusion

In the present work, we examined a novel design methodology (TA-HTDA) for wavelength-routed optical networks wherein, we employed a traffic-aware LTD technique, and a delay-constrained traffic distribution scheme. The traffic-awareness of the LTD scheme has been effected by a prior clustering of the SD pairs in accordance with relative magnitude of their traffic demands (bandwidth). Having grouped the SD pairs into high-traffic and low-traffic clusters, the high-traffic SD pairs were assigned lightpaths using HLDA while low-traffic SD pairs were treated with a recursive version of RLDA. Thereafter the traffic demands between SD pairs were distributed over these lightpaths, using single-hop or multi-hop (concatenated) lightpaths, while satisfying a maximum limit on propagation delay. Our result indicates that the proposed method outperforms the existing design methodologies, more particularly when network needs to support nonuniform traffic distribution. Furthermore, with more stringent constraints on propagation delay the proposed method offers a reasonable solution, while the existing methodologies, such as HLDA and RLDA fail to offer feasible solution (connection) for all the node pairs.

We have also studied all the three algorithms with a recently-procured LP Solver (CPLEX 9.1) used for traffic routing. It is found that LP-based traffic routing offers improved performance for all three LTD algorithms, and even with LP Solver, the proposed TA-HTDA algorithm for LTD with threshold optimization (in cluster formation) offers better performance than HLDA and RLDA.

References

- [1] Biswanath Mukherjee, "WDM Optical Communication Networks: Progress and Challenges," *IEEE Journal on Selected Areas in Communications*, Vol. 18, No. 10, October 2000, pp. 1810-1824.
- [2] R. Ramaswami, and K. N. Sivarajan, *Optical Networks A Practical Perspective*, Morgan Kaufmann Publishers, Second Edition, 2004.
- [3] B. Mukherjee, *Optical Communication Networks*, McGraw-Hill, 1997.
- [4] I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath Communications: An Approach to High Bandwidth Optical WAN's," *IEEE Transactions on Communications*, Vol. 40, No.7, July 1992, pp. 1171-1182.
- [5] R. Ramaswami, and K. N. Sivarajan, "Design of Logical Topologies for Wavelength-Routed Optical Networks," *IEEE Journal on Selected Areas in Communications*, Vol. 14, No. 5, June 1996, pp. 840-851.
- [6] B. Mukherjee, D. Banerjee, S. Ramamurthy, and A. Mukherjee, "Some Principles for Designing a Wide-Area WDM Optical Network," *IEEE/ACM Transactions on Networking*, Vol. 4, No. 5, October 1996, pp. 684-696.