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Fast Routing and Wavelength Assignment
Heuristics for Large-Scale
WDM Optical Networks

by

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Abstract

We consider the routing and wavelength assignment (RWA) problem for large-scale WDM optical networks where each transmission request is served by an all-optical lightpath without wavelength conversion. Two heuristic RWA algorithms are proposed in order to minimize the number of wavelengths required for a given set of connection requests. The proposed algorithms are evaluated and compared with the existing algorithms for two realistic networks constructed based on the locations of major cities in Ibaraki Prefecture and those in Kanto District in Japan.

1 Introduction

A wavelength division multiplexing (WDM) optical network offers a great potential for future high speed applications in large-scale networks because of its wide bandwidth and high-speed data transmission. Data transmission with multiple carrier wavelengths over a single fiber is available using the WDM technology [1, Sect. 1.3.1]. One wavelength is dedicated to each channel between two adjacent nodes on a single fiber link. Data transmission between two nodes in a network can be realized through an all-optical route that traverses a series of links each using an available wavelength.

The optical communication path between a pair of a source and a destination is called a *lightpath*, and it may span multiple fiber links. Without wavelength conversion capability, a lightpath must use the same wavelength on all the links through which it traverses; this property is known as the *wavelength-continuity constraint* [2]. In order to establish a lightpath between a source and a destination, one needs to determine the path (route) from the source to the destination and then assign a wavelength to the path. The problem of routing and wavelength assignment for data transmission is usually known as the *routing and wavelength assignment* (RWA) problem [3, 4].

The RWA problem can be formulated in various forms. In this paper, we consider the RWA problem as a kind of combinatorial optimization with constraints such as a knapsack problem [5]. Our objective is to determine the routing and wavelength assignment in order to minimize the number of wavelengths for a given set of connection requests [1, Sect. 8.2.2]. Algorithms for solving an RWA problem can be either *exact* or *heuristic* [6, 7, 8, 9]. An exact algorithm uses the exhaustive search to find the optimal solution among

all possible combinations of lightpaths which are established for a given set of connection requests [10]. Clearly, it is simple but impractical in terms of the computation time for a large network with a large number of connection requests. On the other hand, a heuristic algorithm provides a good solution to the problem, although it may not be optimal.

In this paper, two heuristic RWA algorithms are proposed, which are the Longest First Alternate Path (LFAP) algorithm and the Heaviest Path Load Deviation (HPLD) algorithm. In LFAP, the RWA problem is formulated as a knapsack problem where lightpaths and wavelengths correspond to items and knapsacks, respectively. The LFAP algorithm assigns a wavelength to a longer lightpath with higher priority and attempts to maximize the number of lightpaths per wavelength. In HPLD, on the other hand, the RWA problem is formulated as a routing problem where the link cost is determined based on the load (utilization) of each link. The HPLD algorithm attempts to re-route some lightpaths that pass through the heaviest link in order to minimize the number of wavelengths.

This paper is organized as follows. Section 2 gives a survey of solutions to the RWA problem. Section 3 presents the network model and problem formulation. Section 4 proposes two heuristic algorithms and shows an illustrative example. Experimental results of the proposed algorithms compared with other existing algorithms are presented in Section 5. Finally, Section 6 gives a summary and some concluding remarks.

2 Early works

The RWA problem of finding the minimum number of wavelengths for WDM networks has been challenging because of its computational complexity. Let

us review some previous works.

Many RWA algorithms are proposed for the ring networks where the nodes are connected fully as a WDM ring [11, 12, 13, 14, 15, 16, 17]. A ring network is special in the sense that the routing is only one of two directions: clockwise or counterclockwise. An algorithm based on the matrix approach was proposed by Ellinas and Bala [11]. In their work, the size of the ring can be increased by adding one node at a time without reassigning wavelengths to the already existing connections. Hunter and Marcenac [12] proposed an optimal wavelength assignment scheme to connect each node to all other nodes on a ring without wavelength conversion. They examined the number of wavelengths required for a WDM ring with up to 16 nodes. Marcenac [13] proposed a simple scheme for wavelength assignment with a random wavelength reuse algorithm. Knoke and Hartmann [14] solved the RWA problem by using a generalized shortest path routing matrix. The matrix is decomposed into sequential wavelength assignment areas so that the global wavelength assignment is simplified and the computational complexity of the algorithm is lowered. Their solution is limited to networks with up to 30 nodes.

Lee et al. [15] used integer programming formulation for the RWA problem on a WDM ring and solved the linear programming relaxation by using the column generation technique. The number of nodes is limited to 20 in their algorithm. Narula-Tam et al. [16] proposed a heuristic joint routing and wavelength assignment algorithm that reduces the average number of wavelengths to map logical topologies. The number of nodes is also limited to 20 in their model. Sahin and Azizoglu [17] proposed a wavelength assignment algorithm based on the general vertex-coloring framework. They obtained the wavelength requirement in a 25-node ring for different numbers of connection

requests.

A few researchers considered the problem of finding the minimum number of wavelengths for arbitrary networks. A simple solution to this problem is to determine the route for each connection request based solely on the smallest number of hops between the source and the destination, but the number of required wavelengths may not be minimized. Chlamtac et al. [18] used a greedy heuristic, called the Longest First Fixed Path (LFFP) algorithm in this paper, to establish all lightpaths with the minimum number of wavelengths. They proposed to assign wavelengths according to the longest lightpath first. Specifically, the shortest paths for a given set of connection requests are sorted in decreasing order and the longest lightpath is assigned a wavelength first. A new wavelength is added for the remaining unestablished lightpaths that cannot be established with the set of already used wavelengths.

Baroni and Bayvel [19] proposed an algorithm, called the minimum number of hops (MNH) algorithm, for minimizing the maximum load per link in arbitrarily connected networks. In MNH, each (s, d) pair of the given set of connection requests is firstly assigned one of its shortest paths. Then, alternate shortest paths are examined for a possible better path and the previously assigned path will be replaced by the alternate path if the load of the most congested link is reduced. This process is repeated for all the (s, d) pairs and stops when no substitutions are possible. The performance of LFFP and MNH algorithms is compared with our algorithms in Section 5.

3 Network Model and Formulation

We introduce a network model for the RWA problem using graph theoretic terminology. Consider an undirected bipartite graph $G = (V, L)$, where V is

the set of vertices representing the network nodes and L is the set of undirected edges representing the bi-directional fiber links in the network. Let $|L|$ denote the number of links in the network. The bi-directional link between nodes u and v is denoted by l_{uv} . The connection request between source-destination pair i is denoted by n_i . The set of connection requests is denoted by $N = \{n_1, n_2, \dots, n_{|N|}\}$, where $|N|$ is the number of connection requests. It is assumed that all the connection requests in the network are specified in advance. The number of wavelengths needed for a given set of connection requests is denoted by F . For convenience, the wavelengths are numbered $1, 2, \dots, F$. We generally have $0 < F \leq |N|$.

Let us consider a lightpath for connection request n_i from node x to node y . Suppose that a lightpath consists of successive links $l_{xv_1}, l_{v_1v_2}, \dots, l_{v_ny}$, where v_1, v_2, \dots, v_n are the intermediate nodes between x and y along the path. Because of the wavelength-continuity constraint, a lightpath can be established only if every link along the path uses the same wavelength. Let j denote the wavelength assigned on the lightpath of request n_i . The remaining connection requests can be established using the same wavelength j only if they have no common links with n_i . Otherwise, another wavelength should be used. The load ρ_{uv} on link l_{uv} is defined as the number of wavelengths used by the lightpaths passing through it. The load of the most loaded link is denoted by ρ_{\max} , which is the number of wavelengths needed for the given set of connection requests in the network.

4 Heuristic Algorithms

In this section, we describe two proposed algorithms LFAP and HPLD in detail. We then illustrate how they work for an example network.

4.1 Longest First Alternate Path (LFAP) Algorithm

The RWA problem can be formulated as a knapsack problem [5, Sect. 8.1], where there are $|N|$ lightpaths (items) and F wavelengths (knapsacks). Let us use the following notation regarding the network model.

C Set of lightpaths that have not yet been established.

c_i i th lightpath; $i = 1, 2, \dots, |N|$.

h_i Number of hops on lightpath c_i ; $i = 1, 2, \dots, |N|$.

$w_j = \begin{cases} 1 & \text{if wavelength } j \text{ is used; } j = 1, 2, \dots, |N|, \\ 0 & \text{otherwise.} \end{cases}$

$p_{ij} = \begin{cases} 1 & \text{if lightpath } c_i \text{ is established using wavelength } j; j = 1, 2, \dots, |N|, \\ 0 & \text{otherwise.} \end{cases}$

E_{ij} Set of links using wavelength j that belong to lightpath c_i .

C'_j Set of the established lightpaths using wavelength j , i.e., $p_{ij} = 1$ for $i \in C'_j$; $j = 1, 2, \dots, |N|$.

R_j Set of lightpaths that cannot be established using wavelength j , i.e., $p_{ij} = 0$ for $i \in R_j$; $j = 1, 2, \dots, |N|$.

L'_j Set of links through which the established lightpaths pass using wavelength j .

$G'_j = (V, L \setminus L'_j)$ Modified graph of $G = (V, L)$.

Z_j Set of connection requests that are not established yet but have alternate paths in network G'_j .

The RWA problem is formulated as a knapsack problem as follows. Wavelengths are treated as knapsacks, each of which can hold more than one lightpath. Lightpaths are treated as items and more than one lightpath can share the same wavelength on condition that no two lightpaths pass through the same link. The RWA problem under consideration is formulated as the following optimization problem:

$$\text{Minimize } F = \sum_{j=1}^{|N|} w_j \quad (1)$$

subject to

$$\sum_{i=1}^{|N|} h_i p_{ij} \leq |L| w_j; \quad j = 1, 2, \dots, |N|, \quad (2)$$

$$\sum_{j=1}^{|N|} p_{ij} = 1; \quad i = 1, 2, \dots, |N|, \quad (3)$$

and

$$E_{ij} \cap E_{kj} = \emptyset; \quad i \neq k. \quad (4)$$

Condition (2) indicates that the number of links using each wavelength may not exceed the total number of links in the network. Condition (3) shows that each lightpath uses only one wavelength. Condition (4) requires that two lightpaths using the same wavelength cannot share the same link in the network. The above problem is clearly NP-hard, thus we propose a heuristic algorithm, called LFAP, to solve this problem.

In LFAP, wavelengths are added one by one until all the lightpaths for the given set of connection requests are established. For each newly added wavelength, the longest lightpath among those of the given connection requests is established. Then, the shorter lightpaths will be checked one by one. If no lightpath can be established, alternate paths are searched. If no lightpath can

be established any more, a new wavelength will be added and the searching process is repeated. After establishing each lightpath, the network topology is modified by removing the links used by the newly established lightpath. That is, the modified graph contains a set of links $L \setminus L'_j$ with the same set of nodes V .

The LFAP algorithm can be described in the following four steps:

Step 1 Initialization. Using a shortest path algorithm, e.g., Dijkstra's algorithm [20, p. 273], find the lightpaths for the given set of connection requests so that each lightpath is the shortest path from the source to the destination. Let $C = \{c_1, c_2, \dots, c_{|N|}\}$, $E_{ij} = \emptyset$ for $i, j = 1, 2, \dots, |N|$, $C'_j = \emptyset$, $R_j = \emptyset$, and $Z_j = \emptyset$ for $j = 1, 2, \dots, |N|$. Let also $j = 1$ and $F = 1$.

Step 2 Wavelength selection. Select the longest lightpath c_i in C . Let $C \leftarrow C \setminus \{c_i\}$ and E'_{ij} be the set of links of the selected lightpath c_i , i.e., $E'_{ij} = \{l_{uv} | l_{uv} \text{ belongs to lightpath } c_i\}$. If $[C'_j = 0]$ or $[E'_{ij} \cap E_{kj} = \emptyset, \forall k \text{ such that } c_k \in C'_j, C'_j \neq \emptyset]$, then let $p_{ij} = 1$, $C'_j \leftarrow C'_j \cup \{c_i\}$, and $E_{ij} = E'_{ij}$, otherwise let $p_{ij} = 0$ and $R_j \leftarrow R_j \cup \{c_i\}$.

Step 3 Stopping criterion. If $C \neq \emptyset$, then go to step 2. Otherwise, if $R_j \neq \emptyset$ go to step 4 else stop the algorithm.

Step 4 Search of the alternate path. Let $L'_j = \bigcup_{i=1}^{|N|} E_{ij}$ and construct the modified network $G'_j = (V, L \setminus L'_j)$. Check whether there exist any shortest paths for the remaining unestablished requests in G'_j . If yes, select the first found shortest paths as the lightpaths for the remaining unestablished requests, add those requests to Z_j , $Z_j \subseteq R_j$, let $C \leftarrow Z_j$ and

$R_j \leftarrow R_j \setminus Z_j$, and then go to step 2. Otherwise, let $C \leftarrow R_j$, $F \leftarrow F + 1$, $j \leftarrow j + 1$ and go to step 2.

4.2 Heaviest Path Load Deviation (HPLD) Algorithm

The HPLD algorithm attempts to deviate the load of the most loaded link to other less loaded path so that the maximum number of wavelengths used in the network is reduced. That is, the HPLD algorithm tries to re-route some lightpaths that pass through the heaviest link. The HPLD algorithm employs the shortest path routing technique to solve this problem based on the network graph G . The weight function of a link (link cost) is determined by the link load. Let $\rho_{\max} = \max\{\rho_{uv}\}$. The mean load $\bar{\rho}$ of a link and the amount Δ of load deviation are calculated as follows:

$$\bar{\rho} = \frac{1}{|L|} \sum_{l_{uv} \in L} \rho_{uv}, \quad (5)$$

$$\Delta = \lfloor \sigma(\rho_{\max} - \bar{\rho}) \rfloor, \quad (6)$$

where $\lfloor x \rfloor$ denotes the largest integer not exceeding x and parameter σ ($0 < \sigma \leq 1$) is used to prevent the algorithm from oscillation by load deviation.

The cost γ_{uv} for using link l_{uv} is given by

$$\gamma_{uv} = \begin{cases} \frac{1}{(\rho_{\max} - 1) - \rho_{uv}}, & \text{if } \rho_{uv} < \rho_{\max} - 1, \\ \infty, & \text{otherwise.} \end{cases} \quad (7)$$

Equation (7) shows that the cost for using a link with light load is cheap but it increases nonlinearly as the link load increases. In order to protect the load deviation from oscillation, it is not allowed that the load of any link is greater than ρ_{\max} after the load deviation.

The HPLD algorithm can be described in the following four steps:

Step 1 Initialization. Using LFFP, determine the lightpaths for the given set of connection requests.

Step 2 Determination of the amount of load deviation. Calculate the mean link load $\bar{\rho}$ and the load deviation Δ by Eqs. (5) and (6). If $\Delta = 0$, then stop the algorithm.

Step 3 Load deviation. Calculate each link cost γ_{uv} using Eq. (7). Select randomly Δ $(s-d)$ pairs whose lightpaths pass through the most loaded link and determine the least-cost path for each selected $(s-d)$ pair. Re-route the lightpaths if they are of finite cost.

Step 4 Stopping criterion. If no load can be deviated, then stop the algorithm. Otherwise, update each link load ρ_{uv} and go to step 2.

4.3 Illustrative Example

Let us illustrate how the LFAP and HPLD algorithms work for an example network consisting of 8 nodes and 11 links shown in Fig. 1. Fifteen connection requests are randomly created as shown in the two left columns of Table 1. The shortest path for each (s,d) pair is determined in terms of the number of hops. For example, for the connection request from node 4 to node 5, the shortest path passes through nodes 2 and 1. The lightpaths are sorted in decreasing order of the path length as shown in the two right columns of Table 1.

With the LFFP algorithm [18], wavelengths are assigned to the paths based on the longest path first. For the example network in Fig. 1, lightpaths 4-2-1-5 and 1-2-4-8 pass the same link 1-2, therefore lightpath 4-2-1-5 uses the first wavelength and lightpath 1-2-4-8 uses the second wavelength. In this way, 6 wavelengths are required in total by the LFFP as shown in Table 2.

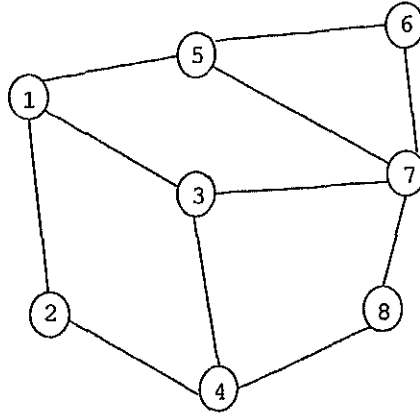


Figure 1: Example of an arbitrary network.

In the LFAP algorithm, for the lightpaths that cannot be established on their shortest paths, their alternate paths are considered before a new wavelength is added. Figure 2 illustrates the assignment of wavelength w_1 by LFAP. Figure 2(1) is the initial stage, and Figs. 2(2)–(6) show the modified graphs after each new lightpath is established until no further lightpath can be established. After assigning w_1 to each lightpath, the occupied links are removed from the graph so that the remaining requests use the modified graph as shown in the figure. When no lightpath can be established further on the modified network, a new wavelength is considered. In this way, 4 wavelengths are needed to satisfy all the required connection requests. The final wavelength assignment by LFAP is shown in Table 3.

In the HPLD algorithm, the initial lightpaths are determined by LFFP as shown in Table 2. Figure 3 shows the process of load deviation (re-routing) by HPLD, where the digits and the numbers in the parentheses on a link denote the number of lightpaths passing through the link and the link cost determined by Eq. (7), respectively. Here, the value of σ is set to 0.8. The thick solid line denotes the heaviest link at each stage during the wavelength

Table 1: Connection requests and the shortest paths.

(s, d)	shortest paths	(s, d)	sorted shortest paths
(3,4)	3-4	(4,5)	4-2-1-5
(5,8)	5-7-8	(1,8)	1-2-4-8
(2,3)	2-1-3	(2,6)	2-1-5-6
(5,6)	5-6	(2,7)	2-1-3-7
(1,4)	1-2-4	(1,4)	1-2-4
(4,7)	4-3-7	(4,7)	4-3-7
(4,5)	4-2-1-5	(3,8)	3-4-8
(3,8)	3-4-8	(5,8)	5-7-8
(1,8)	1-2-4-8	(2,3)	2-1-3
(2,6)	2-1-5-6	(1,7)	1-3-7
(5,7)	5-7	(6,8)	6-7-8
(1,7)	1-3-7	(3,4)	3-4
(6,8)	6-7-8	(5,6)	5-6
(2,7)	2-1-3-7	(5,7)	5-7
(6,7)	6-7	(6,7)	6-7

Table 2: Wavelength assignment by LFFP.

w_1	w_2	w_3	w_4	w_5	w_6
4-2-1-5	1-2-4-8	2-1-5-6	2-1-3-7	1-2-4	2-1-3
4-3-7	1-3-7	3-4-8			
5-7-8	6-7-8				
5-6	3-4				
6-7	5-7				

assignment process. For example, in stage 0 the link l_{12} with load $\rho_{12} = 6$ is the most loaded link. Since $\Delta = 2$, two lightpaths passing through link l_{12} are chosen randomly for re-routing. When stage 2 is reached, we have $\Delta = 0$. The algorithm is then stopped, because no load can be deviated any more. As a result, the wavelength assignment by HPLD is obtained as shown in Table 4, and the number of wavelengths ρ_{\max} equals 4, which is the same as the results by LFAP. However, we have one different route from LFAP. The lightpath for the request of (2,3) pair is 2-4-3 by LFAP while it is 2-4-8-7-3 by HPLD. This is because the HPLD tends to balance the link load values.

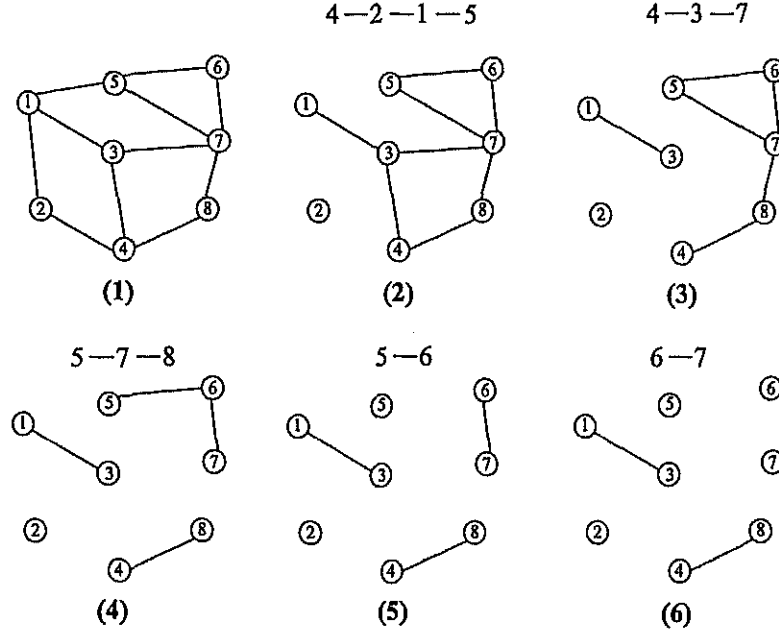


Figure 2: Wavelength assignment of w_1 by LFAP. (1) Initial stage; (2) After assigning lightpath 4-2-1-5; (3) After assigning lightpath 4-3-7; (4) After assigning lightpath 5-7-8; (5) After assigning lightpath 5-6; (6) After assigning lightpath 6-7.

5 Experimental Results

In this section, we examine our heuristic algorithms in comparison with previously proposed algorithms LFFP [18] and MNH [19] for two practical networks.

Network models are constructed by referring to the Nippon Telegraph and Telephone Corporation (NTT) service network. Some major cities in an area in Japan, which are extracted from NTT's public web site (<http://www.ntt-east.co.jp/tariff/ryoukin/>), are selected as the network nodes. Then, by the Delaunay triangulation [20, p. 175] for the set of node locations, we get a fictitious set of links in the network. *Note that the resulting networks are by no*

Table 3: Wavelength assignment by LFAP.

w_1	w_2	w_3	w_4
4-2-1-5	1-2-4-8	2-1-5-6	2-1-3-7
4-3-7	1-3-7	3-4-8	1-5-7-8-4
5-7-8	6-7-8		2-4-3
5-6	3-4		
6-7	5-7		

Table 4: Wavelength assignment by HPLD.

w_1	w_2	w_3	w_4
2-4-8-7-3	1-5-7-8-4	4-2-1-5	1-2-4-8
2-1-5-6	2-1-3-7	1-3-7	6-7-8
3-4	5-6	3-4-8	4-3-7
5-7		5-7-8	
6-7			

means related to the real networks of NTT or any other companies. Given the network topology, we have applied Dijkstra algorithm [20, p. 273] to determine the shortest path for every pair of the source and destination nodes.

5.1 Ibaraki Network

We first consider a network consisting of 14 nodes that represent major cities in Ibaraki Prefecture, which we call Ibaraki network for the sake of convenience, as shown in Fig. 4. In our experiment, the sets of connection requests are randomly generated.

Figure 5 shows the numbers of wavelengths required for a given set of connection requests by using various algorithms. The horizontal axis represents the number of connection requests and the vertical axis represents the number of wavelengths required. It shows that by using alternate paths LFAP, HPLD and MNH can achieve the required number of wavelengths much fewer than LFFP. It can be seen that our algorithms LFAP and HPLD outperform MNH.

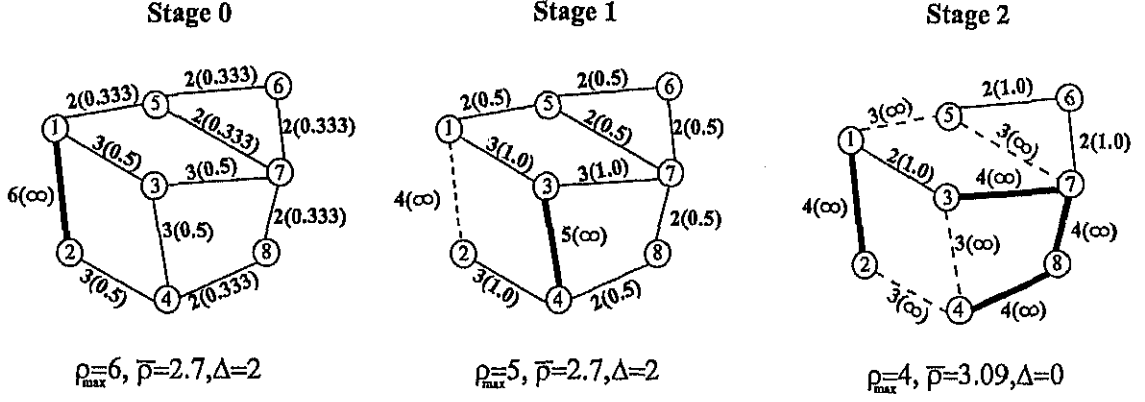


Figure 3: Load deviation (re-routing) process by HPLD.

This is because only the shortest paths are searched in MNH, while not only the shortest paths but also all other possible routes are searched in our algorithms. Therefore, the chance of minimizing the number of wavelengths is higher in our algorithms than in MNH.

In Fig. 6, it is observed that our algorithms LFAP and HPLD show much shorter computation time than MNH. Since in MNH the alternate shortest paths are considered for all (s, d) pairs of the given set of connection requests, it takes a lot of computation time. In LFAP, we consider the alternate paths only for the remaining set of connection requests in the modified graph. In HPLD, we consider only the alternate paths for the connection requests through the heaviest loaded link, which tends to decrease in each stage. Hence, using LFAP and HPLD results in less computation time than MNH.

5.2 Kanto Network

We next examine a network that consists of 82 nodes representing major cities in the Kanto District, which we call Kanto network, as shown in Fig. 7.

It can be seen in Fig. 8 that the performance (the number of wavelengths

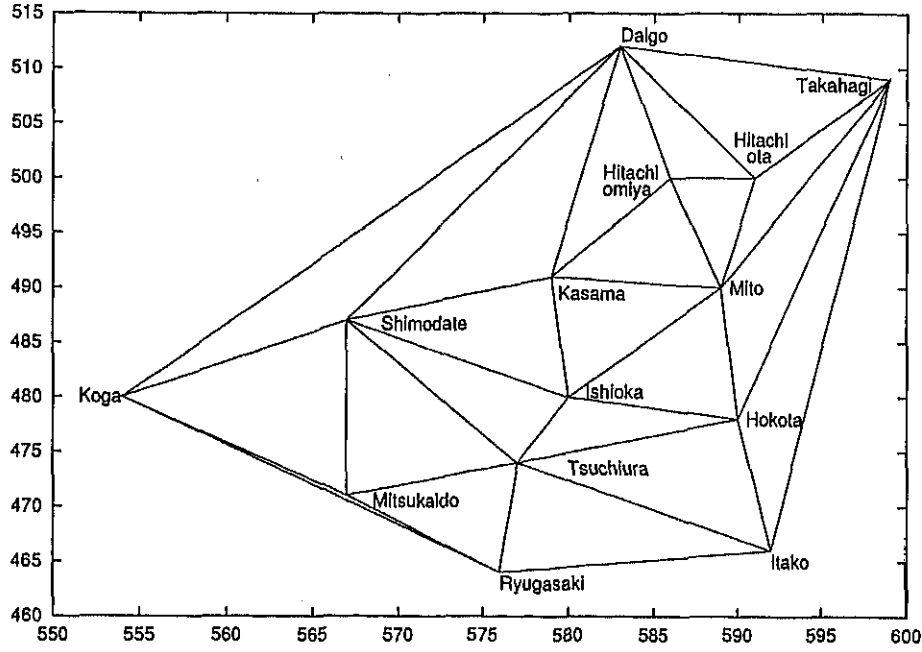


Figure 4: Configuration of the Ibaraki network.

required) of our algorithms LFAP and HPLD is much better than MNH and that HPLD is the best among them. This indicates that the re-routing has a great effect on the performance in large networks.

Figure 9 shows the computational time of the algorithms. It shows that MNH spends more time than any others, since it has to check every alternate shortest path for each connection request in order to minimize the number of wavelengths. For our algorithms, the computation time of LFAP is less than that of HPLD, since the load deviation in HPLD is repeatedly operated and the link cost has to be recalculated in each iteration.

6 Conclusion

In this paper, we have proposed two heuristic RWA algorithms, LFAP and HPLD, in order to minimize the number of wavelengths required for a given

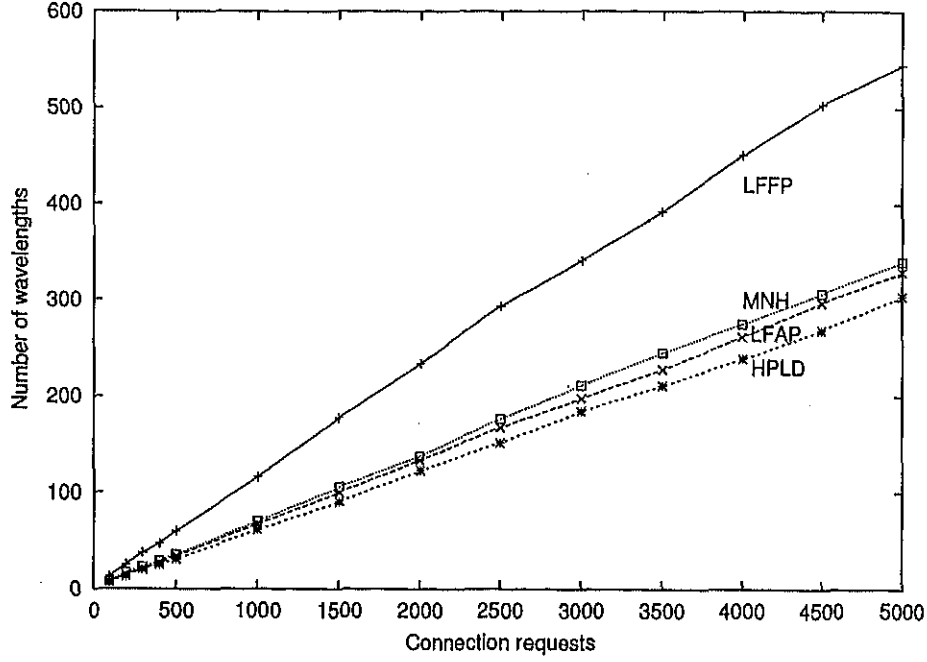


Figure 5: Number of wavelengths required for the Ibaraki network.

set of connection requests. This problem is formulated as a knapsack problem in LFAP and as a routing problem in HPLD. The LFAP and HPLD algorithms are evaluated in comparison with existing algorithms, LFFP and MNH. Our experimental results show that the performance (number of wavelengths required) of LFAP and HPLD is better than LFFP and MNH. The computation time of LFAP and HPLD is much shorter than that of MNH. Furthermore, it has been shown that HPLD yields fewer wavelengths but spends more computation time than LFAP.

A major difference between our algorithms, LFAP and HPLD, and existing algorithms, LFFP and MNH, is the search of alternate paths. In LFFP, no alternate path is considered. Furthermore, alternate paths searched by MNH are limited to the minimum number of hops of all source-destination pairs. For a large-scale network where the number of nodes grows, it will take a long time

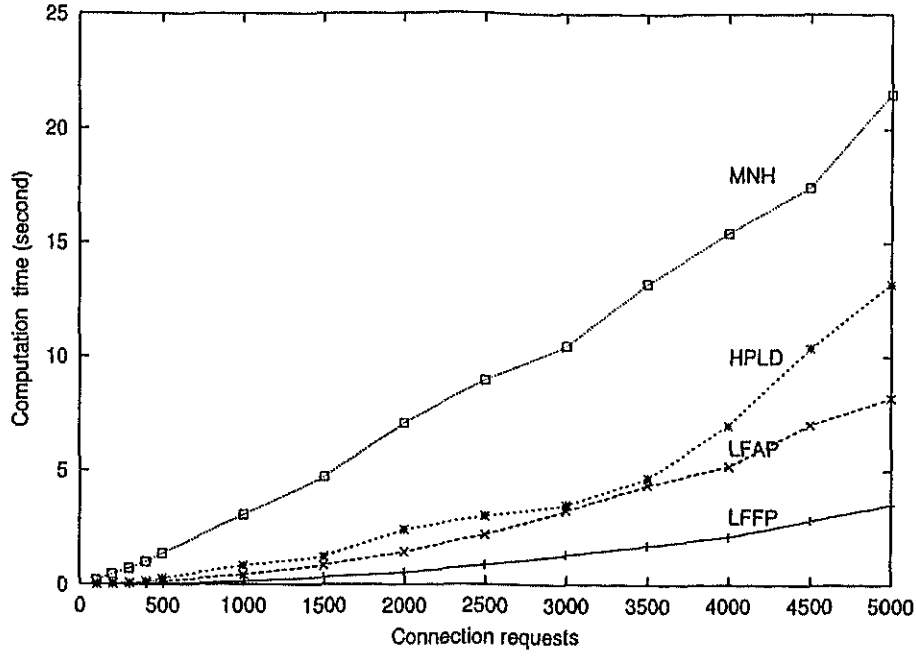


Figure 6: Computation time of the algorithms for the Ibaraki network.

for searching alternate paths. On the other hand, LFAP and HPLD relax the restriction on the path length and therefore can find an alternate path quickly.

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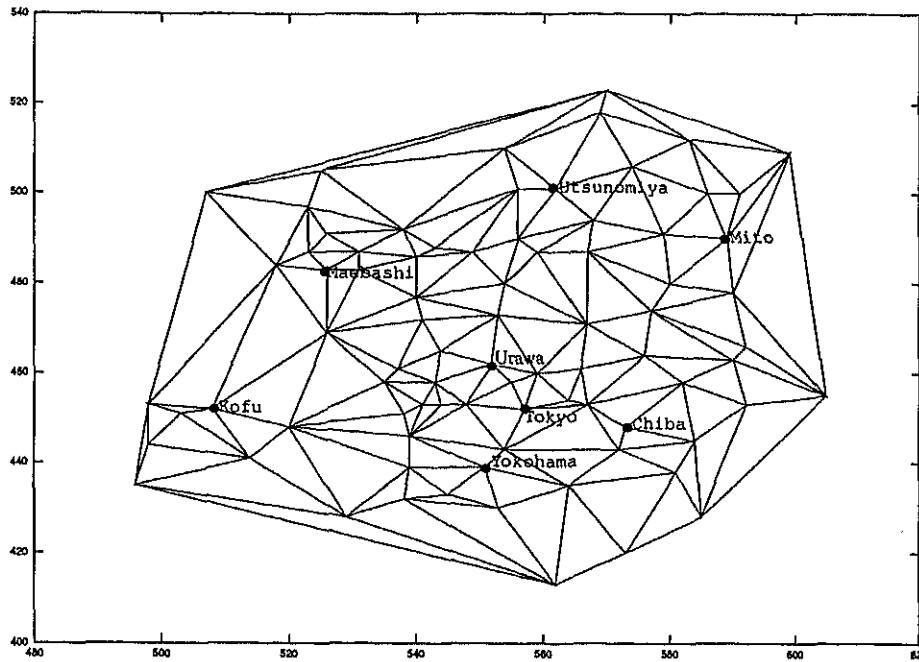


Figure 7: Configuration of the Kanto network.

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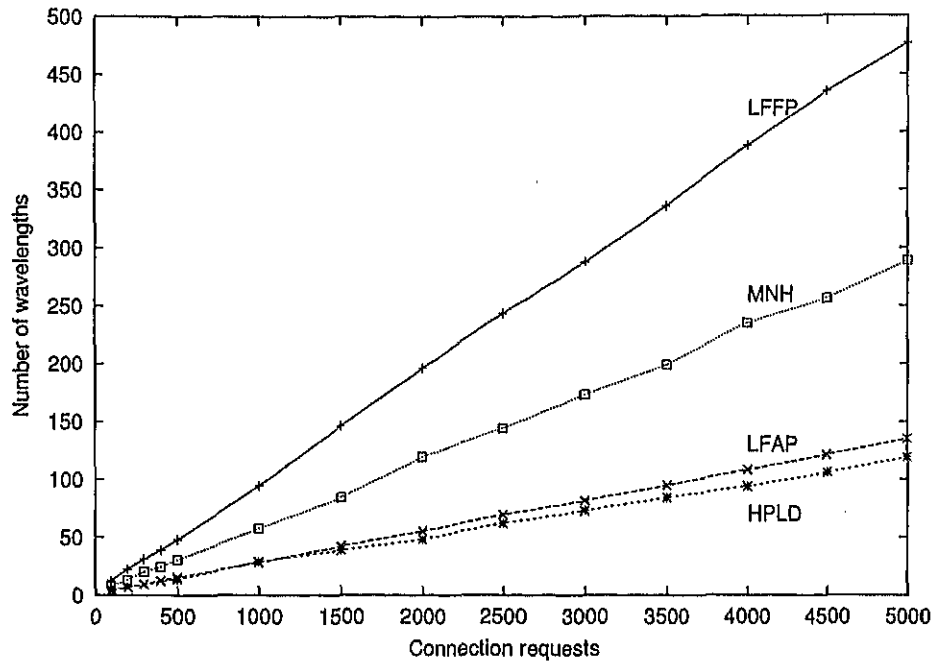


Figure 8: Number of wavelengths required for the Kanto network.

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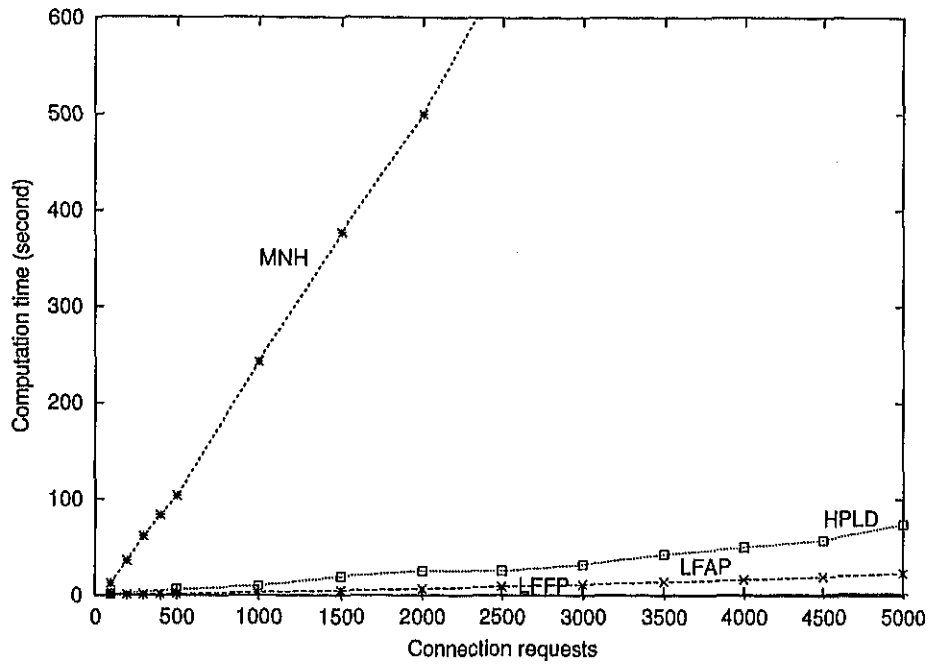


Figure 9: Computation time of the algorithms for the Kanto network.

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