

INSTITUTE OF POLICY AND PLANNING SCIENCES

Discussion Paper Series

No. 1099

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November 2004

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**JAPAN**

# Traffic-based Reconfiguration for Logical Topologies in Large-Scale WDM Optical Networks

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## Abstract

Wavelength division multiplexing (WDM) technology has emerged as a promising technology for backbone networks. The optical layer based on WDM technology provides optical routing services to the upper layers such as the packet switching layer and the time-division multiplexing (TDM) layer over the generalized multi-protocol label switching (GMPLS) paradigm. The set of all-optical communication channels (lightpaths) in the optical layer defines the logical topology for the upper layer applications. Since the traffic demand of upper layer applications fluctuates from time to time, it is required to reconfigure the underlying logical topology in the optical layer accordingly. However, the reconfiguration for the logical topology is reluctantly disruptive to the network since some traffic has to be buffered or rerouted during the reconfiguration process. It therefore needs to have an efficient transition method from the current logical topology to the new one so as to minimize the disruption to the network.

In this paper, we focus on the reconfiguration transition approaches for logical topologies in large-scale wavelength-routed optical networks. We propose several heuristics that move the current logical topology efficiently to the given target logical topology. Our algorithms limit the disruption to the network as little as possible during the reconfiguration process. For this purpose, a lightpath is taken as the minimum unit for the reconfiguration. Our algorithms construct the new logical topology starting from a lightpath with the largest benefit contributed to the reconfiguration. The proposed algorithms are evaluated in comparison with existing algorithms in an NSFNET-like network model with 16 nodes and 25 links. The results show that the proposed algorithms yield much better performance (less disruption to the network) than previous algorithms mostly with comparable computation time.

**Key words:** Lightpath, logical topology, traffic-based reconfiguration, multihop connection, wavelength-division multiplexing, optical networks.

# 1 Introduction

Wavelength division multiplexing (WDM) is a promising technology for using the enormous bandwidth available in an optical communication medium [1, 2]. In a WDM-based network, wavelength multiplexers are utilized to multiplex user signals on a single WDM fiber and optical crossconnects (routing nodes) are used to switch the optical signals in optical domain. Routing nodes with a limited number of optical transmitter and receivers (a pair of a *transmitter* and a *receiver* is called a *transceiver*) are interconnected with each other by point-to-point fiber links. A message arriving at any of the input links of a routing node on some wavelength can be switched to any one of the output links on the same wavelength without electro-optical (E/O) or optical-electronic (O/E) conversion. A route (a set of links) traversed by data between two nodes and formed by an all-optical path on a given wavelength is called a *lightpath*. The wavelength limitation required for an all-optical transmission path is called the *wavelength continuity constraint*. It is virtually impossible to realize the whole connections with all lightpaths due to the resource (wavelength, transceiver, etc.) limitation. Therefore, the data transmission from a source to its destination inevitably needs to pass through more than one lightpath and experiences E/O conversion at intermediate lightpath end-points.

The WDM optical layer in a WDM-based network provides a logical topology comprised of lightpaths to its upper layers such as the packet switching layer and the time-division multiplexing (TDM) layer based on the generalized multi-protocol label switching (GMPLS) control paradigm [3, 4, 5]. In the design of a logical topology for a wavelength-routed WDM network, both the physical fiber network and the network traffic pattern of the upper layers should be taken into account. Since the traffic pattern in upper layers may fluctuate from time to time, it is vital to reconfigure the logical topology according to the changes in the traffic pattern. There are two important issues involved in the reconfiguration of a network logical topology [2, 6, 7, 8, 9]. One is how to determine the target logical topology corresponding to the current topology and traffic pattern. The other is how to determine a reconfiguration transition sequence shifting the current topology to the new one.

In this paper, we focus on the latter problem and propose several reconfiguration algorithms for large-scale WDM optical networks that attempt to move the current logical topology to the given new one while minimizing the disruption to the network. We take a lightpath as the minimum unit in the reconfiguration process and try to determine an optimal establishment sequence for the new lightpaths. Unlike previous studies, we take into account of the rerouted traffic during the reconfig-

uration process. We construct the new logical topology starting from a lightpath with the largest benefit contributed to the reconfiguration. The proposed algorithms are evaluated in comparison with existing algorithms by means of numerical experiments.

The rest of the paper is organized as follows. Section 2 describes the background of this paper and the related work on the logical topology reconfiguration in WDM optical networks. Section 3 presents the problem formulation and the performance measures used in the paper. Section 4 describes the proposed algorithms. Simulation results are shown in Section 5 and the conclusions are summarized in Section 6.

## 2 Background and Related Work

The generalized multiprotocol label switching (GMPLS) is extended from the multiprotocol label switching (MPLS) framework that improves the routing performance over the traditional IP packet switching and provides the quality of service (QoS) required to support realtime multimedia applications [3, 4, 5, 10, 11, 12]. Like circuit-switched networks, MPLS establishes the end-to-end connection path, called the *label switch path* (LSP), between a communication party before transferring data packets. Packets transferred on an LSP are assigned with a label at each intermediate router, called the *label switch router* (LSR). At each hop, the LSR strips off the existing label and applies a new label which tells the next hop LSR how to forward the packets. In GMPLS, wavelengths are used as the labels and utilized to form a logical topology for the upper layers along with the optical LSRs, called the *optical crossconnects* (OXC). The logical topology constructed in the optical layer may change corresponding to the traffic requirements of the upper layers.

The logical topology for a WDM-based network should be designed based on both the physical network topology and the traffic pattern of upper layers [2, 7, 8]. The exact solution to this problem can be easily shown  $\mathcal{NP}$ -hard [13], and therefore heuristic approaches are usually used to find realistic solutions. Furthermore, it is vital to reconfigure the logical topology according to the changes in traffic pattern. However, the reconfiguration is disruptive to the network under operation. It therefore needs to consider a trade-off between the performance of the new logical topology and the cost of the topology reconstruction [8, 9, 14, 15, 16, 17]. Some authors focused on the reconfiguration transition approaches [18, 19, 20, 21]. However, their models are limited to small networks like local area networks.

Banerjee and Mukherjee [8] have studied the reconfiguration issues for logical

topologies in large-scale WDM optical networks. They formulated the reconfiguration problem by using the modified integer linear programming (MILP) formulation and proposed a heuristic algorithm to obtain the new logical topology with the minimum cost. Gencata and Mukherjee [17] proposed an adaptive reconfiguration approach to follow the dynamic changes in traffic patterns without *a priori* knowledge. Their algorithm reacts promptly to the traffic fluctuation by adding or deleting one or more lightpaths at a time. Sreenath *et al.* [9] proposed a two-stage approach to the reconfiguration problem. In the first stage, the reconfiguration is limited to a few changes in order to speed up the reconfiguration process and reduce the reconfiguration cost. In the second stage, the topology optimization between consecutive traffic changes is performed in order to make the topology close to the optimal one.

By using the methods described above, the reconfiguration can be partitioned into several steps so that the difference between the new and old logical topologies at each step is limited. However, we still have the problem of how to realize the new logical topology, i.e., how to move the old logical topology to the new one. Labourdette *et al.* [18] proposed an efficient method, called the *branch exchange*, to shift the old topology to the new one in a local area network like a star-coupler configuration. Under their approach, the reconfiguration sequence is determined clearly and each time only one node pair is selected to switch their transmitters and receivers. Kato *et al.* [22] proposed several reconfiguration algorithms that move the old logical topology to the new one for a torus network. However, their model is based on either star or bus physical networks, i.e., there is no wavelength conflict between the new and old lightpaths. The authors in [23, 24] proposed a reconfiguration method specific to a ring network. Their approach attempts to minimize the disruption to the network and guarantees the connectivity of the network during the reconfiguration process. Recently, the authors in [25, 26] proposed to use a lightpath as the minimum unit to reconfigure the logical topology for large-scale WDM optical networks. They tried to determine a reconfiguration sequence resulting in the minimum disruption to the network resources based on the number of conflict relations between the new and the old lightpaths. However, the performance measures they used are restricted only to the utilization of transceivers and the traffic demand of upper layers is not taken into account.

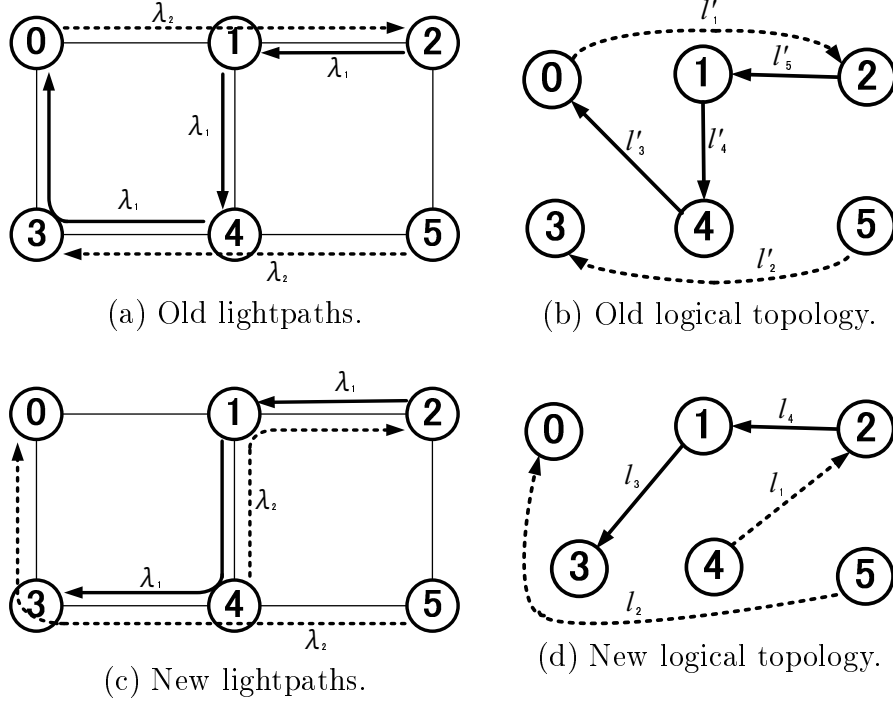


Figure 1: An example of the new and old logical topologies.

### 3 Problem Specification

In a WDM network, each routing node is equipped with add/drop devices and with a limited number of transceivers for data inputs/outputs. A routing node can work as the starting or the ending point of a lightpath. A logical topology for a WDM network is determined based on the traffic demand of upper layers. The reconfiguration for a logical topology is to realize a given new logical topology based on the current (old) logical topology as shown in Figure 1. The lightpaths in the new and old logical topologies are denoted by  $l_i$  ( $i = 1, 2, 3, 4$ ) and  $l'_i$  ( $i = 1, 2, \dots, 5$ ), respectively. The same lightpaths that are used both in the new and old topologies (e.g.,  $l'_5$  in the old logical topology and  $l_4$  in the new logical topology) will remain unchanged. However, the old lightpaths that use any resources, either wavelength, transmitter, or receiver, in conflict with any new lightpath will be reluctantly torn down in order to establish the new lightpath. Since this may cause packet delay or loss, it is crucial to limit the disruption to the network during the reconfiguration process as little as possible.

In this paper, we take a lightpath as the minimum unit for reconfiguration similar to [25]. To establish a new lightpath having conflict relation with any old lightpath, a two-phase procedure is performed. Firstly, the old lightpaths that have conflict

relations with the new one should be torn down. A control message is forwarded to the nodes along the conflicting old lightpaths and let them to release the required resources. Secondly, another control message is forwarded to the nodes along the new lightpath and let them to establish the new lightpath accordingly. Since the time duration for establishing each new lightpath may not vary largely, we assume that the establishment time for any new lightpath is the same and is simply treated as a step of the whole reconfiguration process. Therefore, to reconfigure a new logical topology with  $n$  new lightpaths requires  $n$  steps.

Let  $N$  denote the number of nodes in the network. The numbers of transmitters and receivers at node  $i$  are denoted by  $T_i$  and  $R_i$ , respectively. In this paper, it is assumed that  $T_i = R_i, 1 \leq i \leq N$ . It is also assumed that each transmitter/receiver is tunable to any wavelength range. The set of new lightpaths is denoted by  $S$ . The whole notation used in this paper can be found in Appendix.

In order to minimize the disruption to the network and guarantee the quality of service to the upper layers during the reconfiguration process, an algorithm needs to (1) limit the number of disrupted transceivers, (2) minimize the bias of the number of disrupted transmitters/receivers between the different stages during the reconfiguration operation, and (3) minimize the performance degradation of data transmission in the upper layers. To take these factors into account, we introduce several performance measures. As in our previous research [25], the mean number of disrupted transceivers ( $MDT$ ) is defined as the number of disrupted transmitters/receivers on average at each step during the reconfiguration process and is given by the following relation.

$$MDT = \frac{1}{2|S|} \sum_{i=1}^N \left( \sum_{j=1}^{T_i} t_{ij} + \sum_{j=1}^{R_i} r_{ij} \right),$$

where  $t_{ij}$  and  $r_{ij}$  denote the disrupted time duration (measured in the number of steps) of the  $j$ th transmitter and receiver at node  $i$ , respectively, and  $|S|$  denotes the number of new lightpaths. Note that the disruption time of a transmitter/receiver used only in either the new or the old logical topology is considered to be zero. Therefore, we can formulate an optimization problem for  $MDT$  as follows.

$$\begin{aligned} \min \quad & \frac{1}{2|S|} \sum_{i=1}^N \left( \sum_{j=1}^{T_i} t_{ij} + \sum_{j=1}^{R_i} r_{ij} \right), \\ \text{subject to} \quad & t_{ij}, r_{ij} \geq 0. \end{aligned} \tag{1}$$

The value of  $MDT$  is determined by the establishment order of the new lightpaths and it is generally difficult to find the best establishment sequence. If the reconfiguration sequence is given, the value of  $MDT$  can be calculated as follows. The number of disrupted transceivers at step  $i$  ( $1 \leq i \leq |S|$ ), denoted by  $D_i$ , can be calculated by

$$\begin{aligned}
D_1 &= C_1, \\
D_2 &= D_1 + C_2 - p_1, \\
&\dots \\
D_i &= D_{i-1} + C_i - p_{i-1} \\
&= (C_1 + C_2 + \dots + C_i) - (p_1 + p_2 + \dots + p_{i-1}) \\
&= \sum_{j=1}^i C_j - \sum_{j=1}^{i-1} p_j,
\end{aligned}$$

where  $C_i$  and  $p_i$  denote respectively the numbers of transceivers disrupted and used to establish a new lightpath at step  $i$ . We assume that each new lightpath is established at the end instant of a step and, at each step, only one pair of transceivers is used to establish one lightpath. Therefore, we have  $p_j = 2$  for  $j = 1, 2, \dots, |S|$ . Then, the mean number of disrupted transceivers ( $MDT$ ) is given by the following relation.

$$\begin{aligned}
MDT &= \frac{1}{2|S|} \sum_{i=1}^{|S|} D_i \\
&= \frac{1}{2|S|} \sum_{i=1}^{|S|} \left( \sum_{j=1}^i C_j - \sum_{j=1}^{i-1} p_j \right) \\
&= \frac{1}{2|S|} \left( \sum_{i=1}^{|S|} \sum_{j=1}^i C_j - |S|^2 + |S| \right).
\end{aligned}$$

In order to minimize the bias of the number of disrupted transceivers during the reconfiguration process, we introduce a performance measure showing the maximum instantaneous number of disrupted transceivers ( $MD$ ) as follows:

$$MD = \max_{1 \leq k \leq |S|} \{dis(k)\},$$

where  $dis(k)$  denotes the instantaneous number of disrupted transceivers at the  $k$ th step. To minimize  $MD$ , the following minimization problem can be formulated.

$$\min \max_{1 \leq k \leq |S|} \{dis(k)\}. \quad (2)$$



During the reconfiguration process, the traffic passing through each newly established lightpath  $l_i$  will get some *gain*  $g(l_i)$ , i.e., its delay may become shorter than before. On the other hand, the traffic passing through the disrupted lightpaths has to be rerouted to other lightpaths and that may cause longer delay. This can be considered as the *cost*, denoted by  $c(l_i)$ , for establishing the new lightpath  $l_i$ . The difference of the gain and the cost is defined as the *benefit* for establishing the new lightpath  $l_i$ , denoted by  $B(l_i)$ , and given by

$$B(l_i) = g(l_i) - c(l_i).$$

It is surely preferable to establish a new lightpath yielding the largest benefit with the highest priority. Therefore, we need to find a new lightpath  $l_i$  to establish that satisfies

$$\max_{l_i \in S} B(l_i).$$

For this purpose, we introduce two performance measures, the *weighted packet hop distance* and the *average packet hop distance* as in [8, 9].

The *weighted packet hop distance* for a packet transmitted between a source-destination ( $s$ - $d$ ) pair is defined as the product of the amount of traffic between the ( $s$ - $d$ ) pair and the number of lightpaths (lightpath hops) the traffic passing through. Let  $x$  and  $X$  denote an ( $s$ - $d$ ) pair and the set of all ( $s$ - $d$ ) pairs, respectively. By letting  $T$  denote a certain logical topology, the *weighted packet hop distance* of an ( $s$ - $d$ ) pair  $x$  under topology  $T$ , denoted by  $W_T(x)$ , is given as follows:

$$W_T(x) = \Lambda(x)H_T(x),$$

where  $\Lambda(x)$  and  $H_T(x)$  denote the amount of traffic and the number of lightpaths used for routing the traffic for ( $s$ - $d$ ) pair  $x$ , respectively. The *average packet hop distance*  $\alpha(T)$  under topology  $T$  is defined as the average number of lightpaths that a packet traverses from source  $s$  to destination  $d$  and is given by

$$\alpha(T) = \frac{1}{\sum_{x \in X} \Lambda(x)} \sum_{x \in X} \Lambda(x)H_T(x) = \frac{1}{\sum_{x \in X} \Lambda(x)} \sum_{x \in X} W_T(x).$$

## 4 Proposed Algorithms

It is generally difficult to obtain the optimal reconfiguration sequence for a logical topology in large-scale networks since the possible combinations for lightpath establishment is up to  $|S|!$ . In this paper, we propose to use *heuristic* algorithms

that attempt to minimize the average packet hop distance during the reconfiguration process. That is, at each step of the reconfiguration process the new lightpath yielding the minimum average packet hop distance is selected to establish. For this purpose, an auxiliary graph is introduced to show clearly the conflict relations between the new and old lightpaths. In the following subsections, we first describe how to construct the auxiliary graph and then the proposed algorithms in details.

#### 4.1 Auxiliary graph

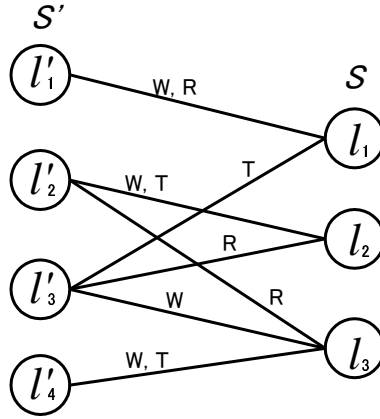


Figure 2: Auxiliary graph.

In the proposed algorithms, the lightpaths in the new logical topology that have no conflict relations with any lightpath in the old logical topology will not be considered. For the conflicting new and old lightpaths, an undirected bipartite auxiliary graph  $G_a(V_a, E_a)$  is introduced, where  $V_a$  and  $E_a$  denote the sets of vertices and edges, respectively. The vertices denote the new and old lightpaths that have conflict relations, i.e.,  $V_a = S \cup S'$ , and the edges denote the specific conflict relations between the new and old lightpaths, i.e.,  $E_a = \{(l_i, l'_j) \mid \text{if } l_i \in S \text{ is in conflict with } l'_j \in S'\}$ .

Note that the conflict relationship may come from the conflicts of wavelength, transmitter, and/or receiver. For example, for the new and old logical topologies shown in Figure 1, we have the conflicting new and old lightpaths as shown in Table 1. Assuming that each node has one transceiver and each link has two wavelengths, the auxiliary graph for Table 1 is created as shown in Figure 2. The conflict relations between the new and old lightpaths due to wavelength, transmitter, and receiver are indicated by  $W$ ,  $T$ , and  $R$  on edges, respectively, as shown in Figure 2. Generally, the auxiliary graph may consist of multiple disjoint components each of which is independent of others. That is, each new lightpath in a component has conflict

relations only with the old lightpaths in the same component and can be established without interference of any lightpath in other components. The algorithms proposed in this paper focus on only one component and they can be used recursively to solve the whole reconfiguration problem.

Table 1: Conflicting new and old lightpaths.

old lightpath	path	wavelength	new lightpath	path	wavelength
$l'_1$	$0 \rightarrow 1 \rightarrow 2$	$\lambda_2$	$l_1$	$4 \rightarrow 1 \rightarrow 2$	$\lambda_2$
$l'_2$	$5 \rightarrow 4 \rightarrow 3$	$\lambda_2$	$l_2$	$5 \rightarrow 4 \rightarrow 3 \rightarrow 0$	$\lambda_2$
$l'_3$	$4 \rightarrow 3 \rightarrow 0$	$\lambda_1$	$l_3$	$1 \rightarrow 4 \rightarrow 3$	$\lambda_1$
$l'_4$	$1 \rightarrow 4$	$\lambda_1$			

## 4.2 Fixed Most-Benefit-First (Fix-MBF) algorithm

Intuitively, a new lightpath leading to more benefit to the reconfiguration should be established earlier. In Fix-MBF, the benefit for establishing a new lightpath is determined by using the initial auxiliary graph and the initial traffic flow pattern. The *gain* obtained from establishing a new lightpath is defined by the reduction quantity in the weighted packet hop distance experienced by the traffic flow passing through the new lightpath. On the other hand, the *cost* for establishing a new lightpath is defined by the incremental delay experienced by the rerouted traffic flow.

The gain function for establishing new lightpath  $l_i \in S$ , denoted by  $g_{fix}(l_i)$ , is defined as the difference of the *weighted packet hop distance* values in the old and new logical topologies before and after establishing lightpath  $l_i$ . Let  $X'$  denote the set of  $(s-d)$  pairs such that a path  $x \in X'$  passes through lightpath  $l_i$ . Furthermore, let  $T_O(l_i)$  denote the logical topology in which only new lightpath  $l_i$  is established over the old logical topology  $T_O$ . Then, we have

$$g_{fix}(l_i) = \sum_{x \in X'} (W_{T_O}(x) - W_{T_O(l_i)}(x)). \quad (3)$$

Conversely, the cost function  $c_{fix}(l_i)$  for establishing new lightpath  $l_i \in S$  is defined as the total incremental delay in the weighted packet hop distance caused by traffic rerouting. Let  $X''$  denote the set of  $(s-d)$  pairs such that a path  $x \in X''$  passes

through old lightpath  $l'_i \in S'$  in conflict relation with  $l_i$ . Then, the cost function is given by

$$c_{fix}(l_i) = \sum_{x \in X''} \left( W_{T_O(l_i)}(x) - W_{T_O}(x) \right). \quad (4)$$

Hence, the *benefit* for establishing new lightpath  $l_i$ , denoted by  $B_{fix}(l_i)$ , is given by the following relation.

$$B_{fix}(l_i) = g_{fix}(l_i) - c_{fix}(l_i). \quad (5)$$

In Fix-MBF, we first calculate the gain  $g_{fix}(l_i)$  and the cost  $c_{fix}(l_i)$  for each new lightpath  $l_i \in S$ . Then, we choose the lightpath with the largest benefit to establish. The Fix-MBF algorithm has the following five steps.

**Step 1.** Create the auxiliary graph  $G_a(V_a, E_a)$  and let  $T = T_O$ .

**Step 2.** Calculate the benefit for establishing each new lightpath using Equation (5).

**Step 3.** Determine lightpath  $\ell$  with the largest benefit in  $S$  such that

$$\ell = \arg \max_{l_i \in S} B_{fix}(l_i).$$

**Step 4.** Set up lightpath  $\ell$ , and update  $T$  and  $G_a(V_a, E_a)$  as follows.

$$\begin{aligned} T &= T + \{\ell\} - N(\ell), \\ S &= S \setminus \{\ell\}, \\ S' &= S' \setminus N(\ell). \end{aligned}$$

**Step 5.** If  $S = \emptyset$ , let  $T_N = T$  and stop. Otherwise, go to Step 3.

### 4.3 Adaptive Most-Benefit-First (Ad-MBF) algorithm

The logical topology of a network along with the traffic flow pattern evolves gradually toward the target logical topology as the reconfiguration process proceeds. Consequently, the gain and the cost of the remaining unestablished lightpaths may change accordingly. It is therefore preferable to select dynamically the best new lightpath to establish. The Ad-MBF algorithm takes into account of the dynamical changes of the logical topology. The weighted packet hop distance for each  $(s-d)$

pair is updated at each step of the reconfiguration process. For a logical topology  $T$  and a new lightpath  $l_i \in S$ , the benefit for establishing lightpath  $l_i$  is defined by

$$B_{ad}(l_i) = g_{ad}(l_i) - c_{ad}(l_i), \quad (6)$$

where

$$\begin{aligned} g_{ad}(l_i) &= \sum_{x \in X'} (W_T(x) - W_{T(l_i)}(x)), \\ c_{ad}(l_i) &= \sum_{x \in X''} (W_{T(l_i)}(x) - W_T(x)). \end{aligned}$$

The Ad-MBF algorithm consists of the following five steps.

**Step 1.** Create the auxiliary graph  $G_a(V_a, E_a)$  and let  $T = T_O$ .

**Step 2.** Calculate/recalculate the benefit  $B_{ad}(l_i)$  for each new lightpath  $l_i \in S$  using Equation (6).

**Step 3.** Determine lightpath  $\ell$  with the largest benefit in  $S$  such that

$$\ell = \arg \max_{l_i \in S} B_{ad}(l_i).$$

**Step 4.** Set up lightpath  $\ell$ , and update  $T$  and  $G_a(V_a, E_a)$  as follows.

$$\begin{aligned} T &= T + \{\ell\} - N(\ell), \\ S &= S \setminus \{\ell\}, \\ S' &= S' \setminus N(\ell). \end{aligned}$$

**Step 5.** If  $S = \emptyset$ , let  $T_N = T$  and stop. Otherwise, go to Step 2.

#### 4.4 Minimal Average packet hop distance lightPath First (MAPF) algorithm

In Ad-MBF, the update of the logical topology is only considered locally to the traffic flow passing through the newly established lightpath and its conflicting old lightpaths. However, each new lightpath may have wider impact on the overall system performance, i.e., the average packet hop distance. The MAPF algorithm recalculates the *average packet hop distance* for each unestablished new lightpath at each step and a new lightpath leading to the minimum average packet hop distance will be selected to establish. For this purpose, the *benefit* for establishing new

lightpath  $l_i$  under logical topology  $T$  is defined as the *negative average packet hop distance* at the next step, i.e., the value of the average packet hop distance after establishing lightpath  $l_i$ , i.e.,

$$B_{ave}(l_i) = -\alpha(T(l_i) + \{l_i\} - N(l_i)). \quad (7)$$

Since the MAPF algorithm recalculates the paths for all the  $(s-d)$  pairs, its computational complexity should be inevitably higher than the previous two algorithms. The MAPF algorithm has five steps as follows.

**Step 1.** Create the auxiliary graph  $G_a(V_a, E_a)$  and let  $T = T_O$ .

**Step 2.** Calculate/recalculate the benefit  $B_{ave}(l_i)$  for each new lightpath  $l_i \in S$  using Equation (7).

**Step 3.** Determine lightpath  $\ell$  with the largest benefit in  $S$  such that

$$\ell = \arg \max_{l_i \in S} B_{ave}(l_i).$$

**Step 4.** Set up lightpath  $\ell$ , and update  $T$  and  $G_a(V_a, E_a)$  as follows.

$$\begin{aligned} T &= T + \{\ell\} - N(\ell), \\ S &= S \setminus \{\ell\}, \\ S' &= S' \setminus N(\ell). \end{aligned}$$

**Step 5.** If  $S = \emptyset$ , let  $T_N = T$  and stop. Otherwise, go to Step 2.

## 5 Numerical Experiments

Numerical experiments have been conducted to evaluate the proposed algorithms in comparison with existing algorithms. The network model used in the experiments is an NSFNET-like network with 16 nodes and 25 links shown in Figure 3. The traffic rates between node pairs for both the new and old logical topologies are randomly created according to two different traffic types: one is uniformly distributed over the range of  $[0, \Gamma C]$  with probability  $p$  ( $0 \leq p \leq 1$ ) and the other is over the range of  $[0, C]$  with probability  $(1-p)$ , where  $\Gamma$  and  $C$  are given constants. In the experiment, the traffic demand from node  $i$  to node  $j$  is distinguished from the demand from node  $j$  to node  $i$ . Therefore, the transmission path for the connection from node  $i$  to node  $j$  is independent of that from node  $j$  to node  $i$ . The logical topology for

a given traffic pattern is determined by using the max multihop (MM) algorithm proposed in [2]. The new logical topology is determined based solely on the given traffic pattern and is independent of the old logical topology. This is because that we expect to evaluate the efficiency of the proposed algorithms when there are a large number of lightpaths needing to reconfigure. In reality, the new logical topology should be designed by taking the old logical topology into consideration.

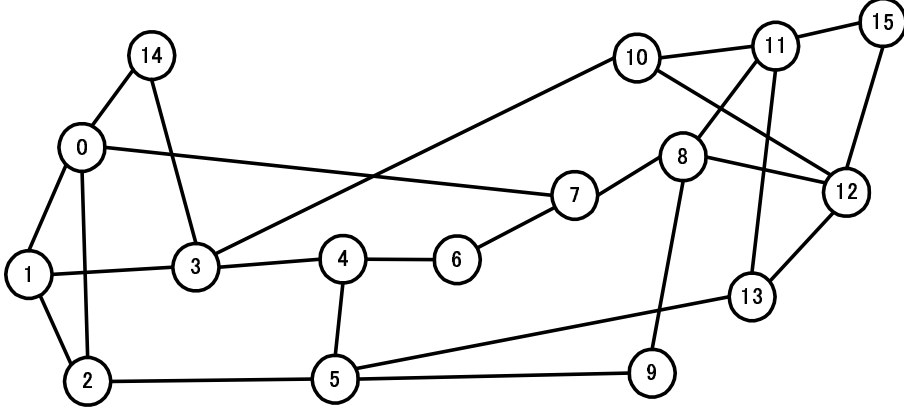


Figure 3: NSFNET-like network model.

It is assumed that each node has wavelength switching functionality. It is also assumed that each node in the network has the same number of transceivers and each link has the same number of wavelengths. In the experiments, we consider the case in which the number of transceivers at a node and the number of wavelengths at a link are all the same and they are denoted by a symbol  $T/R/W$ . The parameter settings used in the experiments are as follows:  $p = 0.3$ ,  $C = 1$ , and  $\Gamma$  is set to 2 and 10, respectively. The parameter  $T/R/W$  is examined with the values one by one from 2 to 10. The simulation program has been developed using JAVA and executed on a LINUX server with two 2.8GHz CPUs.

In order to compare our algorithms with existing algorithms, we implement three algorithms proposed in [25], i.e., the longest lightpath first (LPF) algorithm, the shortest lightpath first (SPF) algorithm, and the minimal disrupted lightpath first (MDPF) algorithm. The LPF algorithm constructs the new lightpaths starting with the longest one and continuing to the shorter ones according to the number of hops of the lightpaths in the physical network. On the other hand, the SPF algorithm constructs the new lightpaths conversely starting with the shortest one. In MDPF, the new lightpath with the minimal number of conflicting old lightpaths is established at each step of the reconfiguration procedure. Interested readers can

refer to [25] for further details in the implementation of these algorithms. The performance measures used for evaluation are, as described in Section 2, the number of disrupted transceivers, the maximum number of disrupted transceivers during the reconfiguration process, and the average packet hop distance. The computation times for executing the algorithms under consideration are also examined.

## 5.1 Computational time

Table 2: Computational time (ms) of the algorithms.

T/R/W	$ S $	LPF	SPF	MDPF	Fix-MBF	Ad-MBF	MAPF
2	26	3.5	3.5	3.7	12.3	100.2	83.0
4	55	7.1	7.3	8.1	27.3	388.4	345.2
5	69	8.8	9.1	10.5	34.9	587.0	545.5
8	113	15.4	15.3	21.3	61.6	1428.8	1467.7
10	141	20.0	19.7	30.9	84.1	2233.9	2407.4

Table 2 shows the number of new lightpaths  $|S|$  having conflict relations with the old lightpaths and the computation times of the algorithms under consideration for various values of  $T/R/W$  when  $p = 0.3$  and  $\Gamma = 10$ . The results shown in Table 2 are the average values obtained from 500 simulation runs each of which has been executed with a distinct traffic pattern.

It can be seen that the number of new lightpaths  $|S|$  and the computation times of the algorithms except Ad-MBF and MAPF increase proportionally to the value of  $T/R/W$ . It is observed that the computation time of LPF, SPF, or MDPF is shorter than either of Fix-MBF, Ad-MBF, or MAPF. Although the computation times of Ad-MBF and MAPF are longer than others in all cases and grow exponentially, they still lie in the practical domain. For example, when  $T/R/W = 10$  (there are over 140 new lightpaths needing to establish), the MAPF algorithm takes only around 2.5 seconds for the whole reconfiguration process. Note that the difference between the new and old logical topologies can be controlled less than the size considered here in practice, and therefore the computation time for reconfiguration should be much shorter than the value shown here. Besides, the most important issue for reconfiguration is how to limit the disruption to the network so that upper layer applications will not perceive the reconfiguration operation.



## 5.2 Comparison of performance

We next evaluate the performance of our proposed algorithms. Since the number of new lightpaths (reconfiguration steps) for each distinct traffic pattern may be different even for the same value of  $T/R/W$ , we normalize the number of reconfiguration steps to one. Therefore, the x-axis of the graphs represents the reconfiguration completion in percentage. The results shown in the figures are the mean values obtained from 500 simulation runs with 95% confidential intervals.

Figures 4 and 5 show the number of disrupted transceivers for the cases where the values of  $T/R/W$  are 5 and 10, respectively. From these figures, it can be seen that the algorithms show similar behaviors for various values of  $T/R/W$  and traffic patterns. The MDPF algorithm yields the best performance as expected and the LPF and SPF algorithms show the worst. From Figures 4(a) and (b), or Figures 5(a) and (b), it is observed that the fluctuation of load has little effect on the performance, i.e., the value of  $MDT$ . Furthermore, the difference of the performance between the MDPF and other algorithms grows larger when the value of  $T/R/W$  becomes larger. Figures 6(a) and (b) show the values of  $MDT$  and  $MD$ , respectively, for various values of  $T/R/W$ . From these two figures, it is observed that  $MDT$  and  $MD$  of each algorithm increases proportionally to the value of  $T/R/W$ . It is observed here again that the LPF and SPF algorithms yield the worst performance compared with others.

Figures 7 and 8 plot the performance measure  $\alpha(T)$  for the algorithms under consideration. The performance of LPF and SPF is largely worse than the others and it is not shown in the figures. From these figures, it is observed that the average packet hop distance  $\alpha(T)$  can be improved by the reconfiguration operation, e.g., the value of  $\alpha(T)$  can be improved from 1.38 to 1.25 as shown in Figure 7(b). As described before, a good algorithm needs to perform the reconfiguration without sacrificing the performance of upper layer applications. From Figures 7 and 8, it is observed that the algorithms proposed in this paper perform not only better than MDPF but provide the performance better than the initial value of  $\alpha(T)$  during the whole reconfiguration process. That means an upper layer user can even perceive the delay reduction during the reconfiguration operation. Furthermore, the performance of Ad-MBF and MAPF is improved greatly within several steps from the beginning. This result is shown clearly when the traffic load is uneven, say, when  $\Gamma = 10$  as shown in Figures 7(b) and 8(b). It is also observed that the performance improvement is more significant when the value of  $T/R/W$  becomes large. During the reconfiguration process, the performance of MDPF may become worse than its

initial performance value because it does not taken into account of the upper layer traffic.

## 6 Conclusion

In this paper, we proposed three reconfiguration algorithms, Fix-MBF, Ad-MBF, and MAPF, that take into account of the traffic demand of upper layers. These algorithms are evaluated by using two kinds of performance measures: one indicating the quantity of disrupted resources, i.e., the mean and the maximum numbers of disrupted transceivers,  $MDT$  and  $MD$ , and the other indicating the user performance, i.e., the average packet hop distance  $\alpha(T)$ . The latter is more important from a user viewpoint and therefore it should be taken into account in reconfiguration with the highest priority. It has been shown that our proposed algorithms show much better  $\alpha(T)$  than existing algorithms. The Fix-MBF algorithm show better performance than existing algorithms and with comparable computation time. Furthermore, the Ad-MBF and MAPF algorithms provide the best performance, and their computation time still falls into practical domain for a moderate-size network even though it is longer than others.

## Acknowledgment

This work is supported in part by the University of Tsukuba under University Research Projects, Research Grant (A) in 2003.

## Appendix

The notation used in this paper is shown as follows.

$l_i$ :  $i$ th lightpath in the new logical topology

$S$ : set of the new lightpaths having conflict relations with the lightpaths in the old topology, i.e.,  $S = \{l_1, l_2, \dots, l_{|S|}\}$

$l'_i$ :  $i$ th lightpath in the old logical topology

$S'$ : set of the old lightpaths having conflict relations with the lightpaths in the new topology, i.e.,  $S' = \{l'_1, l'_2, \dots, l'_{|S|}\}$

$G_a(V_a, E_a)$ : undirected bipartite auxiliary graph where  $V_a = S \cup S'$  and  $E_a = \{(l_i, l'_j) \mid \text{if } l_i \in S \text{ is in conflict with } l'_j \in S'\}$  denote the sets of vertices and edges, respectively.

$T_N$ : target (new) logical topology

$T_O$ : current (old) logical topology

$T(l_i)$ : logical topology in which only new lightpath  $l_i$  is established over logical topology  $T$

$D_i$ : number of disrupted transceivers at step  $i$

$C_i$ : number of the old lightpaths disrupted at step  $i$

$g(l_i)$ : gain obtained from establishing new lightpath  $l_i \in S$

$c(l_i)$ : cost for establishing new lightpath  $l_i \in S$

$B(l_i)$ : benefit obtained from establishing new lightpath  $l_i \in S$

$N(l_i)$ : set of lightpaths having conflict relations with new lightpath  $l_i \in S$

$x$ : an  $(s-d)$  pair

$X$ : set of all  $(s-d)$  pairs

$X'$ : set of  $(s-d)$  pairs that have paths passing through new lightpath  $l_i$  in the new logical topology

$X''$ : set of  $(s-d)$  pairs that have paths passing through old lightpaths  $l'_i$  in conflict relation with  $l_i$

$W_T(x)$ : weighted packet hop distance between an  $(s-d)$  pair  $x$  under logical topology  $T$

$\alpha(T)$  average packet hop distance under logical topology  $T$

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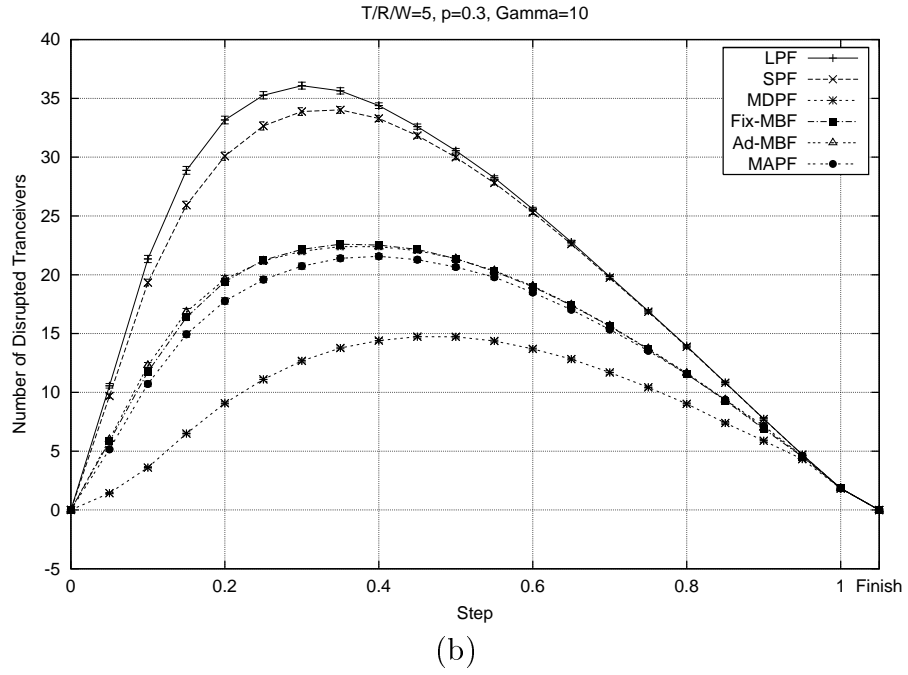
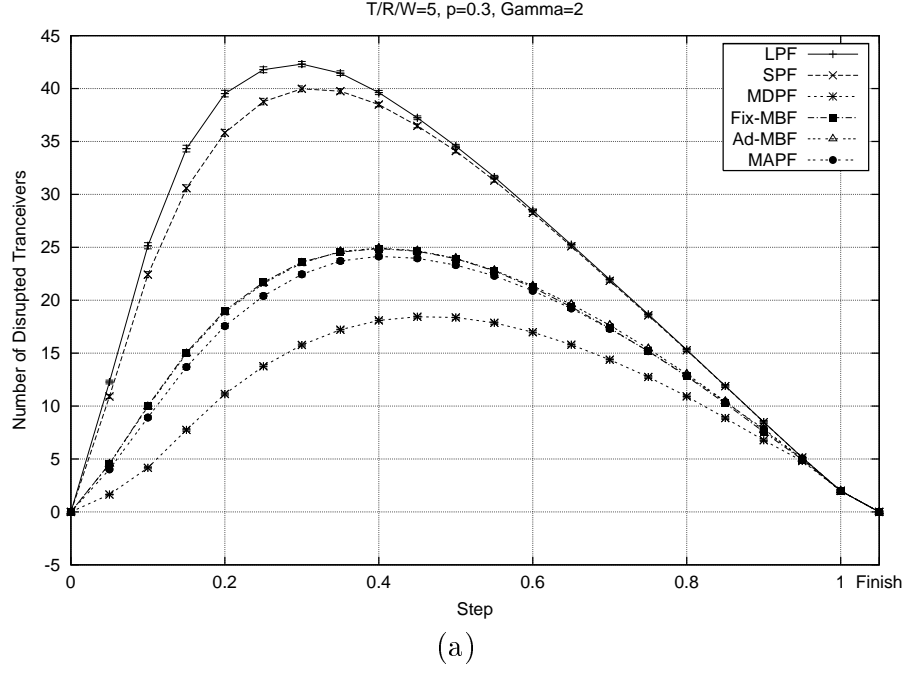


Figure 4: Number of disrupted transceivers for  $T/R/W=5$  when (a)  $p = 0.3$ ,  $\Gamma = 2$ , and (b)  $p = 0.3$ ,  $\Gamma = 10$ .

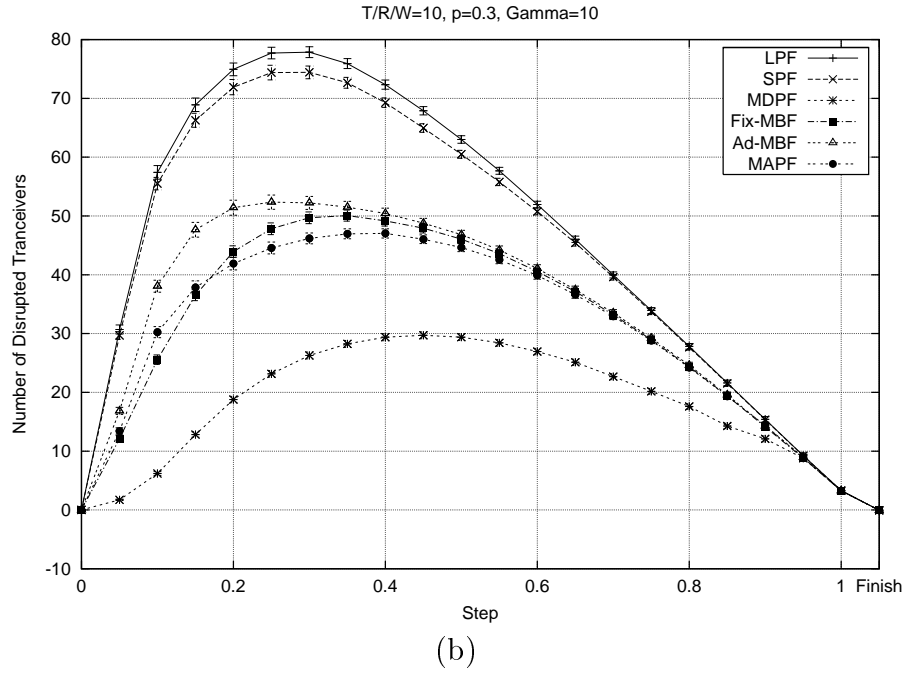
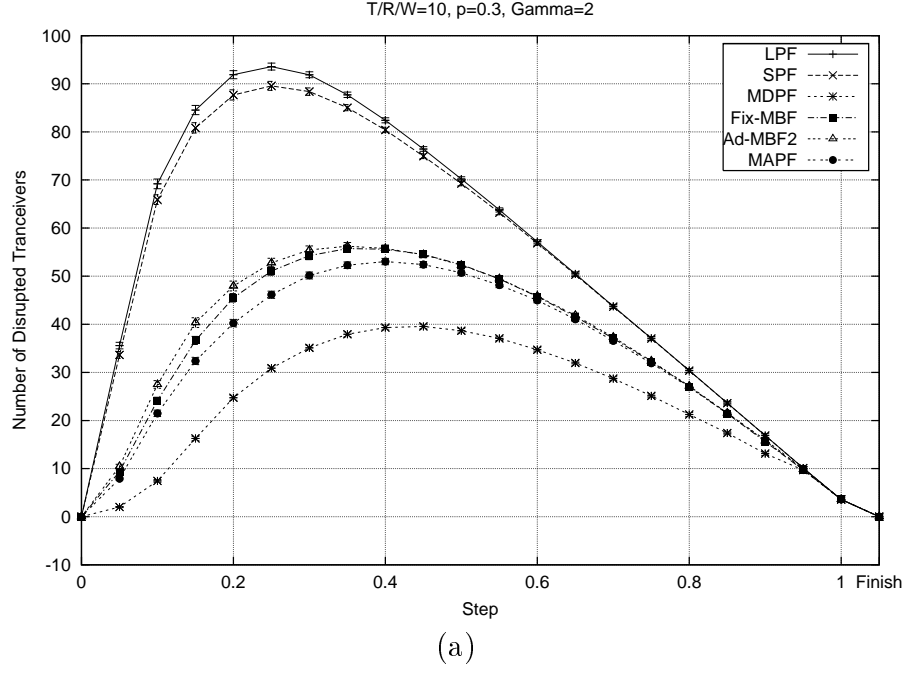


Figure 5: Number of disrupted transceivers for  $T/R/W=10$  when (a)  $p = 0.3, \Gamma = 2$ , and (b)  $p = 0.3, \Gamma = 10$ .

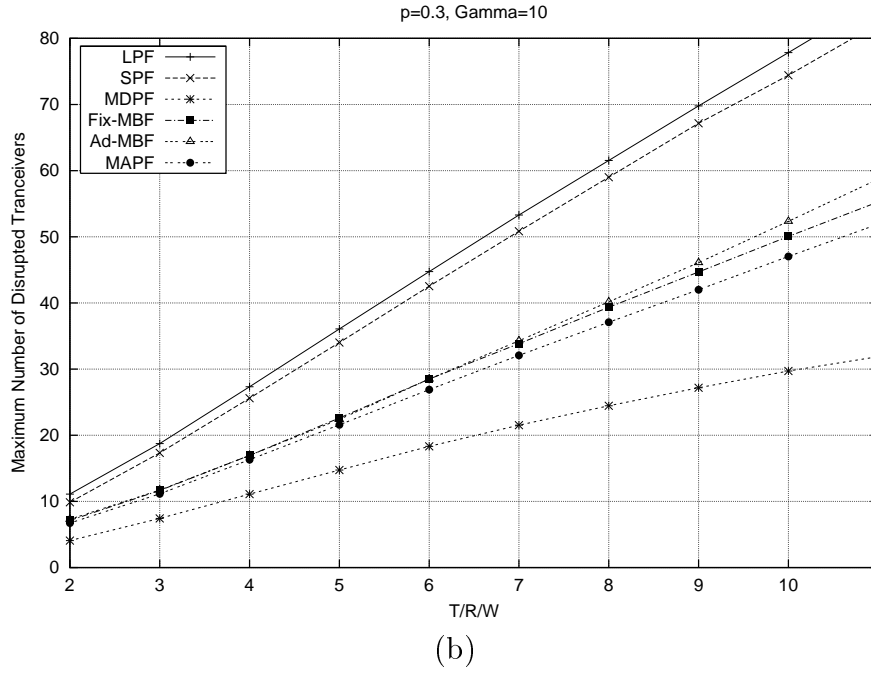
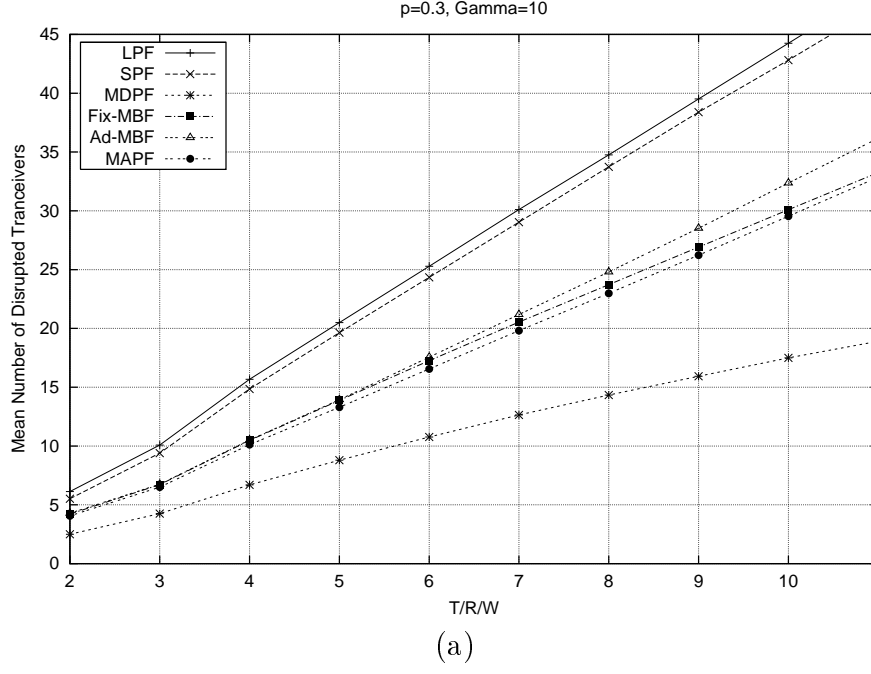


Figure 6: Number of disrupted transceivers for various  $T/R/W$  when  $p = 0.3$  and  $\Gamma = 10$ : (a) mean number of disrupted transceivers ( $MDT$ ) and (b) maximum number of disrupted transceivers ( $MD$ ).



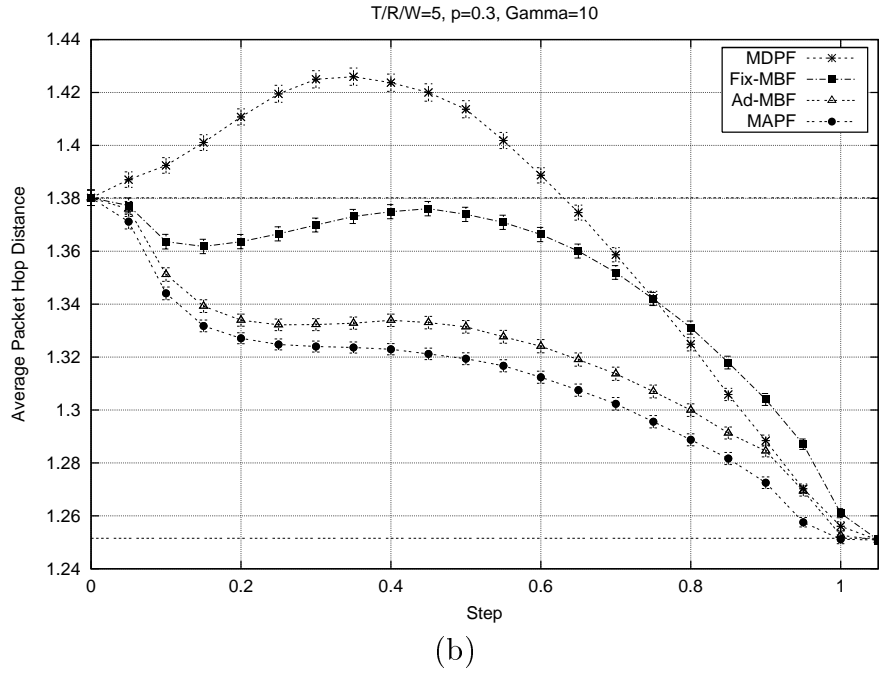
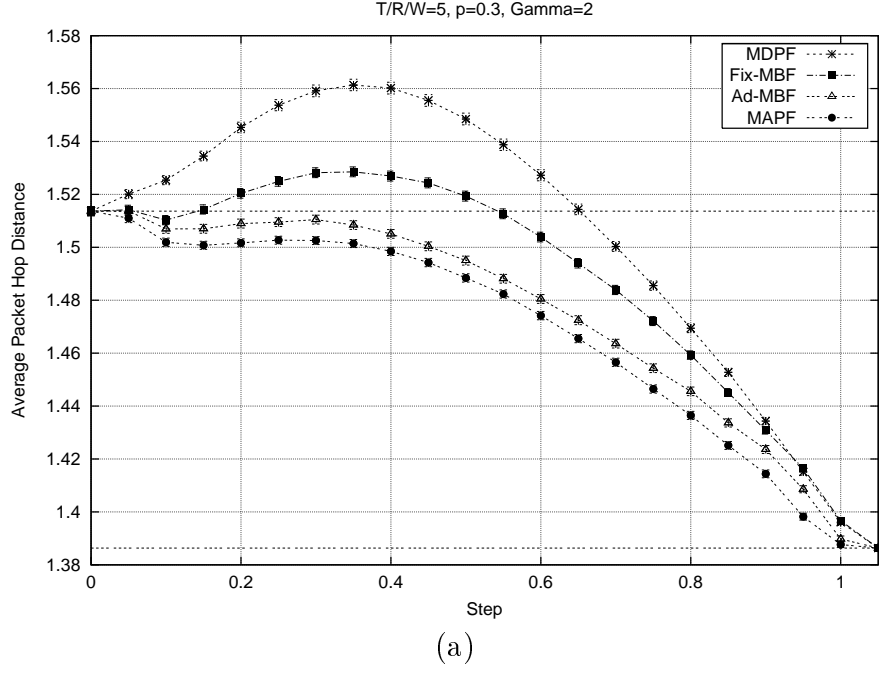


Figure 7: Average packet hop distance for  $T/R/W=5$  when (a)  $p = 0.3$ ,  $\Gamma = 2$ , and (b)  $p = 0.3$ ,  $\Gamma = 10$ .

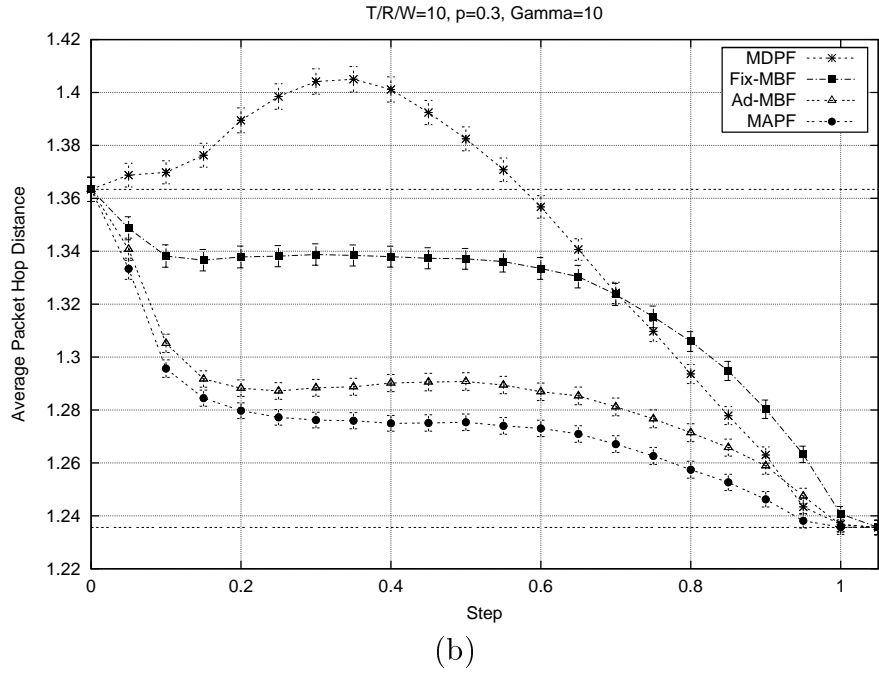
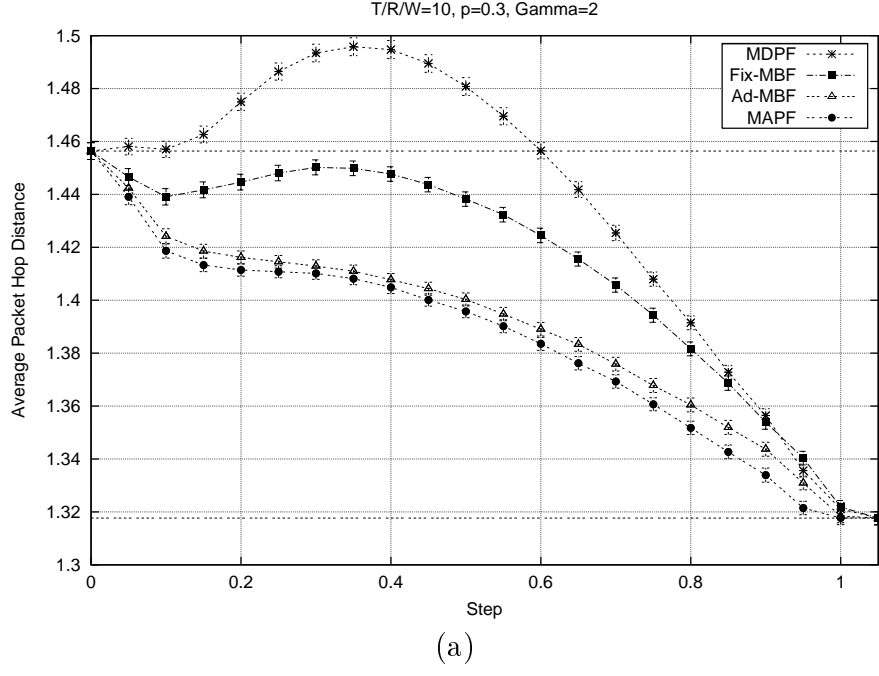


Figure 8: Average packet hop distance for  $T/R/W=10$  when (a)  $p = 0.3$ ,  $\Gamma = 2$ , and (b)  $p = 0.3$ ,  $\Gamma = 10$ .