Allocation of Wavelength Converters in All-Optical WDM Networks with Alternate Routing

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Abstract—This paper proposes a wavelength converter placement method such that the same network will yield low connection blocking probability even when the alternate routing algorithm is replaced by a different one. Since the objective of the alternate routing algorithms used in the networks is to minimize blocking probability, the optimal traffic pattern which minimize the blocked traffic intensity is utilized for finding the locations of wavelength converters. The key idea is to place the wavelength converters at the nodes where they are needed most. Simulations have been performed to study the performance of the proposed wavelength converter placement method. The simulation results have shown that the proposed placement method yields smaller connection blocking probability than the two converter placement methods when the networks employ the hop count based fixed-alternate routing or least-loaded routing.

I. INTRODUCTION

The problem of selecting a given number of nodes in an all-optical WDM network for placement of wavelength converters in order to minimize the connection blocking probability is known as the wavelength converter placement problem. The wavelength converter placement problem has been studied in [1]–[5] for all-optical WDM networks with fixed routing algorithms and in [6] for all-optical WDM networks with alternate routing algorithms. Placement of wavelength converters in an all-optical WDM network with an alternate routing algorithm is more complicated than in a network with a fixed routing algorithm due to the increased complexity and difficulty in estimating the traffic pattern according to the alternate routing algorithm.

In [6], the minimum blocking probability first (MBPF) method was proposed based on the estimated traffic pattern produced by the hop-count based fixed-alternate routing algorithm, and the weighted maximum segment length (WMSL) method was proposed according to the estimated traffic pattern produced by a dynamic-alternate routing algorithm called least-loaded routing algorithm. That is, a specific wavelength converter placement method was designed according to the traffic pattern produced by a given alternate routing algorithm. The drawback of the approach is that the performance of the network may be degraded when the alternate routing algorithm is replaced by an algorithm that is different from that the converter placement method is designed for.

The objective of this paper is to devise a method for placement of wavelength converters in all-optical WDM networks such that the selected locations will yield low connection blocking probability even when the network changes its routing algorithm from one alternate routing algorithm to another. It is expected that a good alternate routing algorithm would try to route the traffic such that the resulting traffic pattern is close to the optimal traffic pattern that minimizes the connection blocking probability. Therefore, a converter placement method that selects the nodes based on the optimal traffic pattern is proposed.

The optimal traffic pattern is used to estimate the amount of traffic intensity that needs to be converted from one wavelength to another at each of the nodes. Based on the optimal traffic pattern, a method to approximate the amount of traffic intensity which needs to be converted from one wavelength to another is proposed. The wavelength converters are placed at the nodes where they are needed most. Simulations are performed to study the performance of the proposed converter placement method. The simulation results show that the proposed method yields lower connection blocking probabilities than the methods proposed in [6] regardless whether the hop-count based fixed alternate routing algorithm or the least-loaded routing algorithm is used in the network.

The rest of this paper is organized as follows. The problem of finding the optimal traffic pattern that minimizes the approximate blocked traffic intensity is formulated as a nonlinear multicommodity flow optimization problem and solved in the next section. A method to calculate the amount of traffic intensity which needs to be converted is proposed in Section III. Performance comparisons are carried out via simulations in Section IV. Finally, some concluding remarks are given in Section V.

II. FINDING THE OPTIMAL TRAFFIC PATTERN

Since the optimal traffic pattern is utilized as a part of the proposed method to find the locations of converters, the optimal traffic pattern needs to be obtained first. In this section, the notations used in formulating the optimization problem are first introduced. Then, the objective function which is the approximate amount of blocked traffic intensity is derived. Finally, the problem is formulated as a nonlinear multicommodity flow optimization problem and solved by a standard optimization technique.

A. Notations

Let \( G = (V, E) \) represent an all-optical WDM network where \( V \) is the set of nodes and \( E \) is the set of links. A link leading from node \( i \) to node \( j \) is denoted by \( l_{ij} \). If there is a link from node \( i \) to node \( j \), there is also a link in the reversed direction. The number of wavelengths provided on each link is denoted by \( W \). The number of converters to be placed in the network is denoted by \( M \).
Let \( P(s, d) = \{P(s, d, k) : k = 1, 2, \ldots, n(s, d)\} \) be the set of link-disjoint routing paths between source node \( s \) and destination node \( d \) where \( P(s, d, k) \) is the \( k \)th routing path and \( n(s, d) \) is the number of link-disjoint paths. The set of link-disjoint routing paths between each source-destination pair is determined in advance by a path finding algorithm such as the \( k \)-shortest link-disjoint paths algorithm. Let \( S(s, d, k) \) be the set of links along routing path \( P(s, d, k) \).

The connection requests for establishing light paths from source node \( s \) to destination node \( d \) arrive at node \( s \) according to the Poisson process with mean arrival rate \( \lambda(s, d) \). The arrival processes of different source-destination pairs are independent. The holding time of each connection is exponentially distributed with mean \( 1/\mu \). The traffic intensity \( \rho(s, d) \) is defined as the ratio of \( \lambda(s, d) \) and \( \mu \).

In the optimization problem, the connection arrival stream for each source-destination pair is to be split probabilistically into a number of substreams each of which is assigned to one of the routing paths. Thus, each of the substreams also forms a Poisson process. Let the portion of \( \lambda(s, d) \) that is assigned to the \( k \)th routing path between source-destination pair \( (s, d) \) be denoted by \( \bar{\lambda}(s, d, k) \). The sum of the connection request rates on all routing paths between source-destination pair \( (s, d) \) must equal to \( \lambda(s, d) \), i.e.,

\[
\lambda(s, d) = \sum_{k=1}^{n(s, d)} \bar{\lambda}(s, d, k), \quad \text{where } s, d \in V \text{ and } s \neq d. \tag{1}
\]

Let the aggregated rate of connection requests that go through link \( l_{ij} \) be denoted by \( \bar{\gamma}(l_{ij}) \) which can be calculated as follows:

\[
\bar{\gamma}(l_{ij}) = \sum_{s \in V} \sum_{d \in V - \{s\}} n(s, d) \sum_{k=1}^{n(s, d)} \bar{I}_{ij}(s, d, k) \bar{\lambda}(s, d, k), \tag{2}
\]

where

\[
\bar{I}_{ij}(s, d, k) = \begin{cases} 1 & \text{if } l_{ij} \in S(s, d, k) \\ 0 & \text{otherwise} \end{cases}. \tag{3}
\]

Let \( \rho_{ij} \) denote the traffic intensity of link \( l_{ij} \) which is defined as \( \bar{\gamma}(l_{ij})/\mu \). Let the connection blocking probability at link \( l_{ij} \) be denoted by \( B_{ij} \).

### B. The Objective Function

Given a network, a set of link-disjoint routing paths between each pair of source-destination nodes, the connection request arrival rate of each source-destination pair, the mean holding time of the connections, the objective is to find the optimal way of splitting the traffic for each source-destination pair onto the multiple link-disjoint routing paths between the source-destination pair such that the overall connection blocking probability is minimized. However, in all-optical WDM networks without wavelength conversion, it is difficult to use the exact or approximate connection blocking probability directly as the objective function in formulating the minimization problem as explained in the previous section. Therefore, an approximation of the amount of blocked traffic intensity is used as the objective function which is closely related to the connection blocking probability.

Since the difficulty in calculating the exact connection blocking probability is the dependency of the states of different links along a routing path and the dependency of the states of different routing paths that share one or more links, the link independent assumption \([7], [8]\) that ignores the dependency among the links as an approximation is employed. With the link independent assumption, each link can be modeled as an M/M/1 queue. The connection blocking probability at link \( l_{ij} \) is the probability that all \( W \) wavelength are occupied, i.e.,

\[
B_{ij} = \frac{\rho_{ij}^W}{W!} \times \frac{1}{\left( \sum_{m=0}^{W} \rho_{ij}^m \right)^W}, \tag{4}
\]

which is the well-known Erlang’s loss formula.

Let the total amount of blocked traffic intensity be denoted by \( \rho_b \). To calculate the total amount of blocked traffic intensity, the amount of blocked traffic intensity on each routing path needs to be calculated first. Let the blocking probability of a connection request on routing path \( p(s, d, k) \) be denoted by \( b(s, d, k) \) which is calculated as follows:

\[
b(s, d, k) = 1 - \prod_{l_{ij} \in S(s, d, k)} (1 - B_{ij}) \tag{5}
\]

Since the product of two or more blocking probabilities of different links is expected to be much smaller than the blocking probability of a single link, these terms are ignored as an approximation. Let \( b(s, d, k) \) denote the approximate value of \( b(s, d, k) \) which is derived from equation (5) as follows:

\[
b(s, d, k) = \sum_{l_{ij} \in S(s, d, k)} B_{ij} = \sum_{l_{ij} \in E} B_{ij} \sum_{l_{ij} \in S(s, d, k)} I_{ij} \tag{6}
\]

Due to the difficulty in calculating the overall connection blocking probability in the entire network, another metric which represents the approximate blocked traffic intensity \( \bar{\rho}_b \) in the entire network is used as the objective function in the optimization problem. The approximate total amount of blocked traffic intensity is obtained by summing over all routing paths; i.e.,

\[
\bar{\rho}_b = \sum_{s \in V} \sum_{d \in V - \{s\}} \sum_{k=1}^{n(s, d)} \frac{n_{sd}}{\mu} \bar{\lambda}(s, d, k) \\
= \sum_{l_{ij} \in E} \sum_{s \in V} \sum_{d \in V - \{s\}} \sum_{k=1}^{n(s, d)} \frac{n_{sd}}{\mu} B_{ij} I_{ij}(s, d, k) \tag{7}
\]

The last equality is due to equation (2). The approximate total amount of blocked traffic intensity, \( \bar{\rho}_b \), is used as the objective function.

### C. The Optimization Problem

The problem of minimizing the approximate total amount of blocked traffic intensity, \( \bar{\rho}_b \), is formulated as the following nonlinear multicommodity flow optimization problem:

Minimize \( \bar{\rho}_b = \sum_{l_{ij} \in E} \frac{\bar{\gamma}(l_{ij})}{\mu} B_{ij} \) \tag{8}

With respect to \( \bar{\gamma}(l_{ij}), \forall l_{ij} \in E \) \tag{9}
Subject to constraints

\[
\begin{align*}
\sum_{k=1}^{n(s,d)} \lambda(s, d, k) &= \lambda(s, d), \quad \forall s, d \in V, \ s \neq d \\
\lambda(s, d, k) &\geq 0, \ k = 1, \cdots, n(s, d), \ \forall s, d \in V, \ s \neq d
\end{align*}
\]

The convexity of the objective function has been proved in [9]. Since the feasible region is a convex set, a local optimum is also a global optimum. The nonlinear multiccommodity flow optimization problem can be solved by the standard optimization techniques [10], [11].

III. FINDING THE AMOUNT OF TRAFFIC INTENSITY WHICH NEEDS TO BE CONVERTED IN EACH NODE

In the proposed method, the amount of traffic intensity which needs to be converted in each node is used to indicate the need of the node to be the converter. The traffic intensity which needs to be converted between an input-output link pair is defined as the portion of traffic intensity passing through the node by the link pair and cannot find the common available wavelength on the link pair while there are available wavelengths on both of the links. The amount of traffic intensity which needs to be converted in a node is obtained by summing over those between all link pairs passing through the node.

To calculate the amount of traffic intensity which requires wavelength conversion between a link pair, a two-link path model as shown in Fig. 1 is employed. The connections passing through a node can be classified into three categories, namely, first-link-only connections, second-link-only connections, and both-links connections. First, an exact markov chain to describe the same two-link path system is proposed and an approximation method to obtain the product form solution of each of the states is provided then. Finally, the product form solution is used to obtained the amount the traffic intensity which needs to be converted of each link pair.

A. Exact Markov Chain

Three categories of connections passing through a node is also used in the proposed method. An example of the two-link path system is shown in Fig. 1. A three-tuple \((n_{ij}, n_{jk}, n_{ik})\) is used to represent a state in the two-link path system where \(n_{ij}\) wavelengths in the first link are occupied by the first-link-only connections, \(n_{jk}\) wavelengths in the second link is occupied by the second-link-only connections, and \(n_{ik}\) wavelengths in both links are occupied by the both-links connections. A state \((n_{ij}, n_{jk}, n_{ik})\) is valid if \(0 \leq n_{ij}, n_{jk}, n_{ik} \leq W\), \(0 \leq n_{ij} + n_{ik} \leq W\), and \(0 \leq n_{jk} + n_{ik} \leq W\). Let \(Y(n_{ij}, n_{jk}, n_{ik})\) denote whether the state \((n_{ij}, n_{jk}, n_{ik})\) is valid or not. That is,

\[
Y(n_{ij}, n_{jk}, n_{ik}) = \begin{cases} 1 & \text{if state } (n_{ij}, n_{jk}, n_{ik}) \text{ is valid} \\ 0 & \text{otherwise.} \end{cases}
\]

The connection requests arrive the two-link path system according to the Poisson process with mean arrival rate \(\gamma_{ij}, \gamma_{jk}, \gamma_{ik}\). Note that the connection request arrival rate is obtained by using equation (2) based on the optimal traffic pattern obtained in the previous section.

For simplicity, let \(n = (n_{ij}, n_{jk}, n_{ik})\) and let \(n_{+}^{+}\) and \(n\) \(n_{-}^{-}\) denote the states \((n_{ij} + 1, n_{jk}, n_{ik})\) and \((n_{ij} - 1, n_{jk}, n_{ik})\) respectively. The same principle is applied to states \(n_{jk}, n\) \(n_{jk}, n_{ik}\), and \(n_{ik}\). Let \(\pi(n)\) denote the steady-state probability of the state \(n\) in the two-link path system. When the two-link path system in a state \(n\) and the even if the state \(n_{ik}\) is also a valid state, not all both-links connection requests can be established due to the wavelength continuity constraint. Therefore, the transition rate from state \(n\) to state \(n_{ik}\) should be modified due to the wavelength continuity constraint. The transition rate from state \(n\) to state \(n_{ik}\) is \(P(n) \times \gamma_{ik}\) where \(P(n)\) is the probability that there is common available wavelength on the two links given in state \(n\). The probability \(P(n)\) can be calculate as follows.

\[
P(n) = \begin{cases} 1 & \text{if } n_{ij} + n_{jk} + n_{ik} < W, \\ 0 & \text{if } n_{ij} + n_{ik} = W, \\ \frac{1}{W - n_{ik}} & \text{if } n_{jk} + n_{ik} = W, \\ \text{otherwise} & \end{cases}
\]

For any valid state \(n = (n_{ij}, n_{jk}, n_{ik})\), let \(\Gamma(n)\) denote the sum of rates leaving the state \(n\). That is,

\[
\Gamma(n) = Y(n; n_{ij}^{+}) \gamma_{ij} + Y(n; n_{jk}^{+}) \gamma_{jk} + Y(n; n_{ik}^{+}) P(n) \gamma_{ik} + Y(n; n_{ij}^{-}) n_{ij} \mu + Y(n; n_{jk}^{-}) n_{jk} \mu + Y(n; n_{ik}^{-}) n_{ik} \mu
\]

The global balance equation for state \(n\) can be written as follows.

\[
\pi(n) = \frac{1}{\Gamma(n)} [ Y(n; n_{ij}^{+}) + (n_{jk} + 1) \mu Y(n; n_{jk}^{-}) + (n_{ik} + 1) \mu Y(n; n_{ik}^{-}) + \gamma_{ij} Y(n; n_{ij}) + \gamma_{jk} Y(n; n_{jk}) + P(n; n_{ik}) \gamma_{ik} Y(n; n_{ik}) \pi(n; n_{ik}^{-}) ]
\]

The markov chain can be solved numerically by a standard technique [12].

B. The proposed approximation method

It is very difficult to find a product form solution for the exact markov chain since the markov chain is not time reversible [12]. In this section, an approximation method to obtain a product form solution for the markov chain is used. It is hoped to modify the exact markov chain to be time-reversible such that the product form solution for the steady-state probability of each state can be easily obtained [12].

The main idea is that the transition rate of between the all valid states \((n_{ij}, n_{jk}, n_{ik})\) and \((n_{ij}, n_{jk}, n_{ik} + 1)\) is adjusted such that the new markov chain is time reversible and the steady state probabilities in the two markov chains is as close as possible. In the exact markov chain, the transition rate from...
state \((n_{ij}, n_{jk}, n_{ik})\) to state \((n_{ij}, n_{jk}, n_{ik} + 1)\) depends on the state \((n_{ij}, n_{jk}, n_{ik})\) which makes the markov chain is not time reversible. In order to let the modified markov chain be time reversible, let the transition rates from state \((n_{ij}, n_{jk}, n_{ik}, c)\) to state \((n_{ij}, n_{jk}, n_{ik}, c + 1)\) be the same for all \(n_{ij}, n_{jk}\) where \(c\) is an integer constant between 0 and \(W\). The transition rate from state \((n_{ij}, n_{jk}, n_{ik})\) to state \((n_{ij}, n_{jk}, n_{ik}, c+1)\) for all \(n_{ij}, n_{jk}\) pair is denoted as \(\gamma_{ik}^c(c)\).

Note that the steady state probability of state \((n_{ij}, n_{jk}, n_{ik})\) in the exact markov chain is denoted as \(\pi(n_{ij}, n_{jk}, n_{ik})\). Let \(\pi'(n_{ij}, n_{jk}, n_{ik})\) denote the steady state probability of state \((n_{ij}, n_{jk}, n_{ik})\) in the approximate markov chain. The main idea of the approximation method is that sum of the transition rates between two different number of both-links connections, \(n_{ik}\), does not change. In the exact markov chain, the equation can be written down as follows.

\[
\sum_{i=0}^{W-c-1} \sum_{j=0}^{W-c-1} \pi(i, j, c) \gamma_{ik}^c(c) = \sum_{i=0}^{W-c-1} \sum_{j=0}^{W-c-1} P(i, j, c) \pi(i, j, c) \gamma_{ik}^c(c) \tag{16}
\]

In the approximate markov chain, the equation is as follows.

\[
\sum_{i=0}^{W-c-1} \sum_{j=0}^{W-c-1} \pi'(i, j, c) \gamma_{ik}^c(c) = \sum_{i=0}^{W-c-1} \sum_{j=0}^{W-c-1} P(i, j, c) \pi'(i, j, c) \gamma_{ik}^c(c) \tag{17}
\]

In order to find \(\gamma_{ik}^c(c)\) such that the steady state probabilities \(\pi(i, j, c)\) and \(\pi'(i, j, c)\) for all \(i, j\) can be as close as possible, let \(\pi'(i, j, c) = \pi(i, j, c)\) for all \(i, j\). That is,

\[
\sum_{i=0}^{W-c-1} \sum_{j=0}^{W-c-1} \pi'(i, j, c) \gamma_{ik}^c(c) = \sum_{i=0}^{W-c-1} \sum_{j=0}^{W-c-1} P(i, j, c) \pi'(i, j, c) \gamma_{ik}^c(c) \tag{18}
\]

Then, consider the markov chain when the number of both-links connections is fixed, \(c\). Since the first-link-only connections and second-link-only connections are independent, the steady state probability can be write as follows.

\[
\pi'(i, j, c) = \gamma_{ij}^c \gamma_{jk}^c \pi'(0, 0, c) \quad \forall \ 0 \leq i, j \leq W - c \tag{19}
\]

Substitute equation (19) into equation (18), the equation is as follows.

\[
\sum_{i=0}^{W-c-1} \sum_{j=0}^{W-c-1} \gamma_{ij}^c \gamma_{jk}^c \pi'(0, 0, c) \gamma_{ik}^c(c) = \sum_{i=0}^{W-c-1} \sum_{j=0}^{W-c-1} P(i, j, c) \gamma_{ij}^c \gamma_{jk}^c \pi'(0, 0, c) \gamma_{ik}^c(c) \tag{20}
\]

Thus, the transition rate \(\gamma_{ik}^c(c)\) can be calculated as follows.

\[
\gamma_{ik}^c(c) = \frac{\sum_{i=0}^{W-c-1} \sum_{j=0}^{W-c-1} P(i, j, c) \gamma_{ij}^c \gamma_{jk}^c}{\sum_{i=0}^{W-c-1} \sum_{j=0}^{W-c-1} \gamma_{ij}^c \gamma_{jk}^c} \gamma_{ik}^c \tag{21}
\]

In the approximate markov chain, the steady state probability for the state \((n_{ij}, n_{jk}, n_{ik})\) can be calculated as follows.

\[
\pi'(n_{ij}, n_{jk}, n_{ik}) = \sum_{i=0}^{n_{ij}} \sum_{j=0}^{n_{jk}} \sum_{k=0}^{n_{ik}} \frac{\gamma_{ij}^0 \gamma_{jk}^0 \prod_{z=0}^{k-1} \gamma_{ik}^z(z)}{k! \mu^{k}} \pi'(0, 0, 0) \tag{22}
\]

where

\[
\pi'(0, 0, 0) = \sum_{i=0}^{W} \sum_{j=0}^{W} \sum_{k=0}^{W} \frac{\gamma_{ij}^0 \gamma_{jk}^0 \prod_{z=0}^{k-1} \gamma_{ik}^z(z)}{k! \mu^{k}} \tag{23}
\]

After obtaining the steady state probabilities, the probability, which is denoted as \(\gamma_{ik}^c(c)\), that there is no common available wavelength on the input-output link pair \((l_{ij}, l_{jk})\) while there are available wavelengths on both of the input and output links can be calculated as follows where \(P(n_{ij}, n_{jk}, n_{ik})\) is defined in equation (13).

\[
\pi_{ik}^c = \sum_{n_{ij} + n_{ik} < C} \sum_{n_{jk} + n_{ik} < C} \{\pi(n_{ij}, n_{jk}, n_{ik}) \times [1 - P(n_{ij}, n_{jk}, n_{ik})]\} \tag{24}
\]

The traffic intensity which requires wavelength conversion between the link pair \((l_{ij}, l_{jk})\) through node \(c\) can be calculated as \(\rho_{ik}^c \times \pi_{ik}^c\) where \(\rho_{ik}^c\) is the accumulated traffic intensity of the connections which use both of the two links.

Finally, the traffic intensity \(\rho\) which requires wavelength conversion in node \(j\) is calculated as the sum of such traffic intensities \(\rho_{ik}^c\) over all link pairs \((l_{ij}, l_{jk})\) passing through node \(j\). That is,

\[
\rho = \sum_{i \in V} \sum_{k \in E} \sum_{l_{ij} \in E} \rho_{ik}^c \times \pi_{ik}^c \tag{25}
\]

The traffic intensity which requires wavelength conversion on each node is then used to place the converters. The main idea of this method is to place the converters in the nodes which really needs to be converted from one wavelength to another. For each node \(j\), the traffic intensity which passing through node \(j\) and requires wavelength conversion is computed by the method described in equation (25). The nodes are sorted in descending order according to the traffic intensity which requires wavelength conversion. The first \(M\) nodes are selected to be the locations of converters where \(M\) is denoted as the number of converters to be placed in the network.

IV. SIMULATIONS

The proposed method is compared via simulations with the two converter placement methods proposed in [6], namely, minimum blocking probability first (MBPF) and weighted maximum segment length (WMSL) methods, which are designed according to the traffic patterns produced by the hop-count based fixed-alternate routing algorithm and least-loaded routing algorithm respectively. Each data point of the simulation results is the average connection blocking probability over 20 50-node random graphs generated using the GT-ITM [14] tool. The number of wavelengths, \(C\), on each link is 24. The maximum number of link-disjoint routing paths between each source-destination pair is 3.
Figs. 2 and 3 respectively show the connection blocking probabilities of the converter placement methods for all-optical WDM networks with hop-count based fixed-alternate routing and least-loaded routing. The following observations can be made according to the figures:

- Neither the MBPF method nor the WMSL method is able to always yield lower connection blocking probabilities than the other when different alternate routing algorithms are used in the networks. In other words, the performance of a network is degraded when the network employs an alternate routing algorithm that is different from that the converter placement method is designed for.

- The proposed method yields lower connection blocking probabilities than the MBPF and WMSL methods regardless whether the hop-count based fixed-alternate routing or least-loaded routing is used as the routing algorithm. In other words, the proposed converter placement method is able to produce lower connection blocking probability than the MBPF and WMSL methods when the routing algorithm is changed from the hop-count based fixed-alternate routing to the least-loaded routing and vice versa.

V. CONCLUSIONS

In this paper, a converter placement method for all-optical WDM networks with alternate routing algorithm has been proposed. The proposed converter placement method has been shown to be able to produce low connection blocking probability even when the routing algorithm is changed from one alternate routing algorithm to a different alternate routing algorithm. The simulation results have shown that the proposed method yields lower connection blocking probabilities than both the minimum blocking probability first (MBPF) and weighted maximum segment length (WMSL) methods proposed in [6] regardless whether the hop-count based fixed-alternate routing or the least-loaded routing is used as the routing algorithm. In other words, the proposed converter placement method is able to produce low connection blocking probability when the routing algorithm is changed from the hop-count based fixed-alternate routing to the least-loaded routing and vice versa. The performance of the proposed method will be evaluated in networks with other alternate routing algorithms in the future works.

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