## Short Paper

# Performance Assessment of Fuzzy Logic Control Routing Algorithm with Different Wavelength Assignments in DWDM Networks*

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DWDM (Dense Wavelength Division Multiplexing) is an effective technique to make use of the large amount of bandwidth in optical fibers to meet the broadband requirement of multimedia applications. The routing and wavelength assignment (RWA) algorithm efficiently manages optical network resources and is separated from the optical topology. This paper proposes a dynamic LLR algorithm using fuzzy logic control (FLC LLR) with different wavelength assignments. The unexpected traffic load is increased when the traffic load is high and the lightpath is long for the LLR routing algorithm. How to balance the traffic load of each link and minimize the hop count for each lightpath is considered. The fuzzy logic control in the FLC LLR algorithm is based on the traffic load and hop count to determine whether the lightpath can be established. Simulation results show that the FLC LLR algorithm has better performance than the LLR algorithm in terms of connection, blocking probability and channel utilization, especially when the traffic load is high. We also show that the FLC LLR algorithm increases the number of connections to be set up without incrementing the channel utilization. The number of conversions are compared as three wavelength assignments embedded in the FLC LLR algorithm when the converters are considered.

***Keywords:*** DWDM, RWA, FLC LLR algorithm, system performance, traffic load

## 1. INTRODUCTION

DWDM (Dense Wavelength Division Multiplex) [1, 2], is an efficacious technology for carrying different wavelengths on one optical fiber. It has been an indispensable communication technique for the Internet and high speed transmission systems. Networks with optical cross-connects and WDM technology are referred to as wavelength routed networks. In the DWDM network, a lightpath can be established by the same or different wavelengths available on all links between the source nodes and the destination nodes. The routing and wavelength assignment (RWA) problem [3, 4] is to select a pos-

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sible path and wavelength in each connection given a set of connection requests. Two network traffic patterns are discussed, static traffic [5-7] and dynamic traffic [8-10]. Most works focus on the dynamic traffic case, in which the connection requests arrive at random and lightpaths are set up on demand. Many studies showed that the RWA problem with or without converters is known to be NP-complete or nearly so [5]. As a result, one of the better dynamic wavelength routing algorithms, the Least Loaded Routing (LLR) Algorithm [10], is proposed to increase the network throughput by balancing the traffic load among the alternate paths without loading any of them to the point of congestion. The LLR algorithm is adaptive and is an application of the shortest path algorithm (*Dijkstra*'*s algorithm*). It is different from hop by a hop routing algorithm that uniforms to use the minimum traffic load of links as a cost function [10, 11], instead of hop count, to reduce the blocking probability of connection establishments. Unfortunately, the hop count based on the LLR algorithm is still high and causes some unexpected traffic load to offset the merits of the LLR algorithm. So, how to balance the traffic load of each link and minimize the hop count for each path is considered in this paper.

The scenario used in this paper is categorized into two parts. For the first part, the LLR algorithm with fuzzy logic control (LLR FLC) is proposed to mitigate the problem of unexpected traffic load of the LLR algorithm during the lightpath connections. The membership functions on the LLR FLC use fuzzy sets based on the traffic load of each link and the hop count of the routing path, and then applies the fuzzy rules to determine whether the lightpath can be established or not. Then, the system performance of three wavelength assignment algorithms (First-Fit, Random [8, 10] with and without converters and Least converter, count [3, 5] with converters) with the LLR FLC are evaluated and compared. The First-Fit algorithm assigns a number to the index of each wavelength and chooses the wavelength based on a sorting. When the indexes of wavelengths are sorted in increasing order, the selected wavelength centers of smaller wavelength numbers cause the utilization and assignment of wavelength to be unbalanced. The Random algorithm selects the wavelength arbitrarily and judges whether it can meet the routing requests. Due to randomness, the wavelength assignment is more uniform than the sorting algorithm. Both random and first-fit algorithms have a high number of wavelength conversions and increase the end-to-end delay time. Another better algorithm, the Least converter count, takes the wavelength conversion times into consideration. It checks any available wavelengths in the source node, and then the number of conversion times is increased by one if no channel is available. After collecting all information, the path with the fewest wavelength conversions from the source node to the destination node is selected to decrease the blocking probability and the end-to-end delay time**.**

The rest of the paper is organized as follows. Section 2 describes the proposed LLR FLC algorithm. Section 3 evaluates system performance with and without converters using computer simulation in terms of connection setups, blocking probability and channel utilization. The conclusion is given in section 4.

## 2. FLC LLR ALGORITHM

The FLC LLR algorithm is used to decrease the block probability and minimize the hop count for each lightpath. The LLR algorithm selects the routed wavelength pair for each connection based on the current network's status. The fuzzy logic control routing algorithm is used to evaluate the relation between traffic load of each link and hop count during selection of lightpaths.

### 2.1 The Model Assumptions and Cost Function

The model assumptions and definition of cost function are described as follows:

1. The topology is a mesh network.
2. All control information is obtained by central management.
3. There are $Y$ links in the network. Each link $Y_j$ holds only one fiber, $j = 1, \ldots, n$, and there are $W_i$ channels in each fiber, $i = 1, \ldots, m$, respectively. If $W_i$ is used on a link, then the indicator $UM_i$ is equal to 1; otherwise it is 0.
4. The traffic load on the given link is $L_i = \sum_{i=1}^{m} UM_i / m.$ (1)
5. Each node has a converter that is capable of switching to all different channels.
6. The fuzzy sets and membership functions for traffic load and hop count and the appropriate fuzzy set limits are obtained by the simulation results.
7. The cost function per link is defined by the number of channels used and can be expressed as $\sum_{i=1}^{m} UM_i$.

### 2.2 Fuzzy Set and Membership Function of Traffic Load Along a Lightpath

The membership function based on the fuzzy set depends on the traffic load and hop count along a lightpath. The traffic load ratio is defined in (1), and the membership function of traffic load along a lightpath is defined as the sum of cost functions to the total number of channels from the source to the destination. The Membership degree vs. traffic load along a lightpath is defined in Table 1 and the membership function of traffic load along a lightpath is shown in Fig. 1.

**Table 1. Membership degree of traffic load along a lightpath.**

| Membership degree | Traffic load |
|---|---|
| *LVS* (Load Very Small) | 0% to 20% |
| *LS* (Load Small) | 10% to 50% |
| *LM* (Load Middle) | 30% to 70% |
| *LH* (Load High) | 60% to 90% |
| *LVH* (Load Very High) | 80% to 100% |

The fuzzy set for each membership function of traffic load is

$$F_{LVS} = \begin{cases} 1, & X\% \le 10\% \\ -\dfrac{X}{10} + 2, & 10\% < X\% < 20\% \end{cases}, \quad F_{LS} = \begin{cases} \dfrac{X}{20} - \dfrac{1}{2}, & 10\% < X\% \le 30\% \\ -\dfrac{X}{20} + \dfrac{5}{2}, & 30\% < X\% < 50\% \end{cases},$$

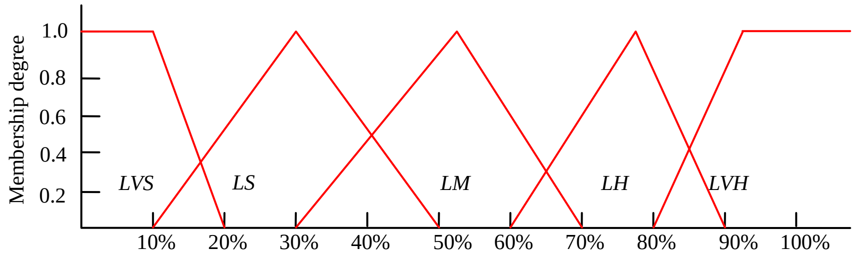



Fig. 1. Membership function of traffic load along a lightpath.

$$F_{LM} = \begin{cases} \frac{X}{30} - 1, & 30\% < X\% \le 60\% \\ -\frac{X}{10} + 7, & 60\% < X\% \le 70\% \end{cases}, \quad F_{LH} = \begin{cases} \frac{X}{15} - 4, & 60\% < X\% \le 75\% \\ -\frac{X}{15} + 6, & 75\% \le X\% < 90\% \end{cases},$$

$$F_{LVH} = \begin{cases} \frac{X}{10} - 8, & 80\% < X\% \le 90\% \\ 1, & 90\% < X\% \le 100\% \end{cases}.$$

## 2.3 Fuzzy Set and Membership Function of Hop Count

The membership degree vs. hop count is defined in Table 2 and the membership function of hop count is defined in Fig. 2. The membership function of hop count is defined as the hop count from the source to the destination to the total number of links minus one. The reason is that the cycle must be avoided by the total number of links in the network minus one in a worst case. The fuzzy set for each membership function of hop count is

$$F_{HVS} = \begin{cases} 1, & X\% \le 10\% \\ -\frac{X}{10} + 2, & 10\% < X\% < 20\% \end{cases}, \quad F_{HS} = \begin{cases} \frac{X}{10} - 1, & 10\% < X\% \le 20\% \\ -\frac{X}{10} + 3, & 20\% \le X\% < 30\% \end{cases},$$

$$F_{HM} = \begin{cases} \frac{X}{15} - \frac{4}{3}, & 20\% < X\% \le 35\% \\ -\frac{X}{15} + \frac{10}{3}, & 35\% < X\% \le 50\% \end{cases}, \quad F_{HH} = \begin{cases} \frac{X}{20} - \frac{1}{2}, & 35\% < X\% \le 60\% \\ -\frac{X}{15} + 5, & 60\% < X\% \le 75\% \end{cases},$$

$$F_{HVH} = \begin{cases} \frac{X}{10} - 7, & 70\% < X\% \le 80\% \\ 1, & 80\% < X\% \le 100\% \end{cases}.$$

**Table 2. Membership degree of hop count.**

| Membership degrees | Hop count |
|---|---|
| *HVS* (Hop Very Small) | 0% to 20% |
| *HS* (Hop Small) | 10% to 30% |
| *HM* (Hop Middle) | 20% to 50% |
| *HH* (Hop High) | 35% to 75% |
| *HVH* (Hop Very High) | 70% to 100% |

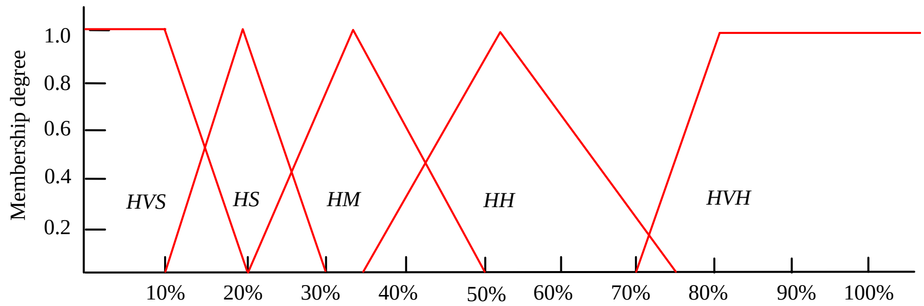



Fig. 2. Membership function of hop count.

## 2.4 Fuzzy Rules

Table 3 shows the fuzzy rules of lifetime for each connection, $R^{(g)}$ ($g$ = 1, 2, …, 25), using if-then rules constructed by fuzzy sets {*LVS*, *LS*, *LM*, *LH*, *LVH*} in the membership function of traffic load and {*HVS*, *HS*, *HM*, *HH*, *HVH*} in the membership function of hop count as its universal set. Our proposed algorithm reduces the unexpected traffic load when the LLR algorithm fails to select the connection with the larger hop count. For example, when the degree of traffic load is *LVS* and the degree of hop count is *HH* or *HVH*, the connection request fails, or when the degree of traffic load is *LVH* and the degree of hop count is *HVH*, the connection request also fails. The exceptions are that when both the degree of traffic load is *LH* or *LVH* and the degree of hop count is *HH*, the connection request is granted. The reason is that it is hard to find another better connection when the traffic load is heavy near the current connection.

The defuzzification method is based on Centriod Defuzzification [13] and calculates the appropriate parameter of fuzzy limit. If the value after defuzzification is greater than the fuzzy limit, the connection request succeeds; otherwise, the connection request fails. When connection request fails, the selected path may be too long or the mean traffic load may be too heavy. The flowchart of the FLC LLR algorithm is shown in Fig. 3.

## 2.5 An Example of the Tradeoff between Network Load and Hop Count

In this section, we discuss how to balance the traffic load of each link and minimize the hop count for each path. For example, there are ten nodes, fifteen links; and each link

**Table 3. Fuzzy rules.**

| Fuzzy rules | | Traffic Load | | Hop Count | | Connection |
|---|---|---|---|---|---|---|
| $R^{(1)}$ | if | *LVS* | and | *HVS* | then | 1 |
| $R^{(2)}$ | if | *LVS* | and | *HS* | then | 1 |
| $R^{(3)}$ | if | *LVS* | and | *HM* | then | 1 |
| $R^{(4)}$ | if | *LVS* | and | *HH* | then | 0 |
| $R^{(5)}$ | if | *LVS* | and | *HVH* | then | 0 |
| $R^{(6)}$ | if | *LS* | and | *HVS* | then | 1 |
| $R^{(7)}$ | if | *LS* | and | *HS* | then | 1 |
| $R^{(8)}$ | if | *LS* | and | *HM* | then | 1 |
| $R^{(9)}$ | if | *LS* | and | *HH* | then | 0 |
| $R^{(10)}$ | if | *LS* | and | *HVH* | then | 0 |
| $R^{(11)}$ | if | *LM* | and | *HVS* | then | 1 |
| $R^{(12)}$ | if | *LM* | and | *HS* | then | 1 |
| $R^{(13)}$ | if | *LM* | and | *HM* | then | 1 |
| $R^{(14)}$ | if | *LM* | and | *HH* | then | 0 |
| $R^{(15)}$ | if | *LM* | and | *HVH* | then | 0 |
| $R^{(16)}$ | if | *LH* | and | *HVS* | then | 1 |
| $R^{(17)}$ | if | *LH* | and | *HS* | then | 1 |
| $R^{(18)}$ | if | *LH* | and | *HM* | then | 1 |
| $R^{(19)}$ | if | *LH* | and | *HH* | then | 1 |
| $R^{(20)}$ | if | *LH* | and | *HVH* | then | 0 |
| $R^{(21)}$ | if | *LVH* | and | *HVS* | then | 1 |
| $R^{(22)}$ | if | *LVH* | and | *HS* | then | 1 |
| $R^{(23)}$ | if | *LVH* | and | *HM* | then | 1 |
| $R^{(24)}$ | if | *LVH* | and | *HH* | then | 1 |
| $R^{(25)}$ | if | *LVH* | and | *HVH* | then | 0 |

has four channels a cost function as shown in Fig. 4. At first, when a connection between node 1 and node 3 is requested, LLR algorithm finds the lightpath, node 1 → node 4 → node 5 → node 8 → node 9 → node 10, which has the minimum costs. The hop count is 5 and the sum of cost function is 5. So the degrees of hop count and traffic load are 35.7% (5/(15 − 1)) and 25% (5/20), where the denominator is 20 because there are 5 links and each link has 4 channels. According to the fuzzy set and membership function of hop counts, we can calculate that the membership degree of the hop count is $F_{HH}$. The membership degree of the traffic load calculated from the fuzzy set and membership function of traffic load is $F_{LS}$. Based on the fuzzy rule, we can find that the resulting connection is false. Finally, the connection setup fails.

## 3. SIMULATION RESULTS

The simulation environment is based on the NSFNet that is constructed by 16 nodes and 21 links; the number of channels is 8 or 16. The traffic load is dynamic. The system

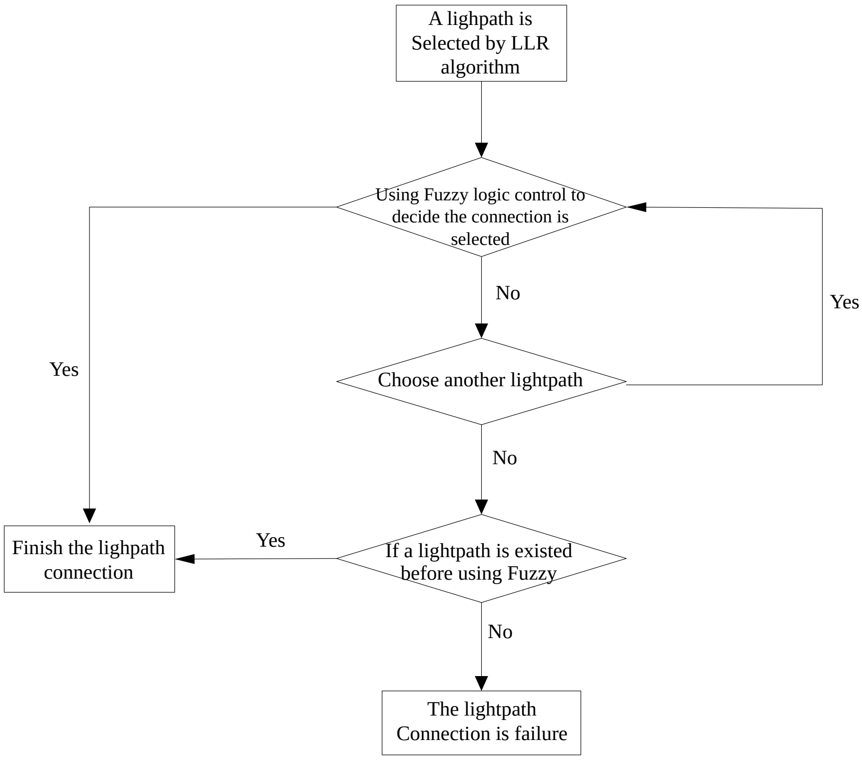



Fig. 3. FLC LLR algorithm flowchart.

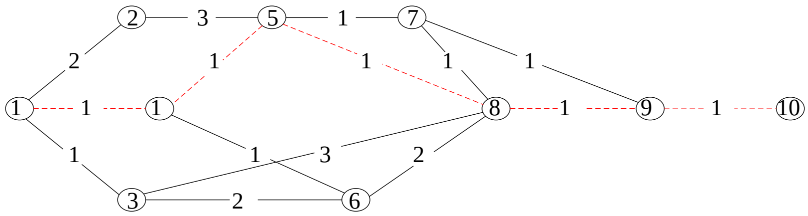


Fig. 4. Using cost Function to execute LLR algorithm.

performance of the three algorithms *without* converters, LLR, hop by hop and FLC LLR, are compared in terms of the number of success feel connections, blocking probability and channel utilization in the first-fit and random wavelength assignment algorithms. Furthermore, the blocking probability with and without converters and the number of conversions are evaluated for three wavelength assignment algorithms, first-fit, random and least converter count *with* converters embedded in the FLC LLR. The membership functions and fuzzy rules are defined in section 2. In [12], we show that the simulation results have no clear improvement when the fuzzy limit is between 0.5 and 0.8. So the fuzzy limit is set to 0.8 or 0.9. The saturation time T is the duration time when the channel utilization is 100% by the LLR algorithm.

### 3.1 Connections Setup

Fig. 5 (a) shows simulation results of the number of successful connections for the three routing algorithms, FLC LLR, LLR and Hop by Hop algorithms without converters using first-fit wavelength assignment algorithm. Note that the number of successful connections for the algorithms is LLR > FLC LLR > Hop by Hop when the saturation time is below 0.3*T*. The reason is that the unexpected traffic load with the LLR algorithm is low when the traffic load is below 0.3*T*. But when the saturation time is more than 0.4T, the number of successful connections is FLC LLR > LLR > Hop by Hop. The unexpected traffic load with the LLR algorithm is high when the connections of paths are longer after the traffic load got heavy. Defuzzification with the FLC LLR algorithm can alleviate the problem when the saturation time is more than 0.5T. On the other hand, the number of successful connections with the FLC LLR algorithm increases by 10% more than with the LLR algorithm when the number of channel is 16 and the saturation time is 0.9*T*. The same simulation result for the random wavelength assignment algorithm is shown in Fig. 5 (b). Overall, the simulation result shows that the first-fit algorithm performs better than that of the random algorithm, and we find that the FLC LLR algorithm has more successful connections for a heavier traffic load and more channels.

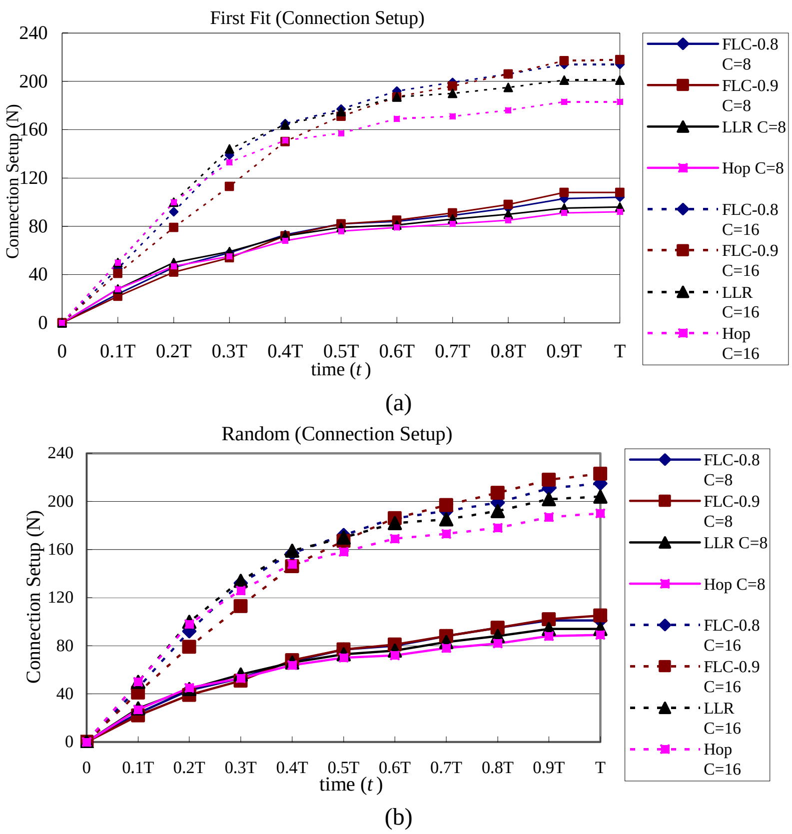
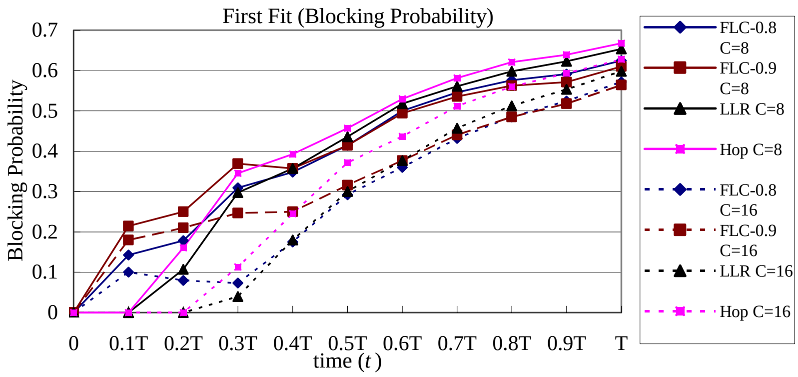


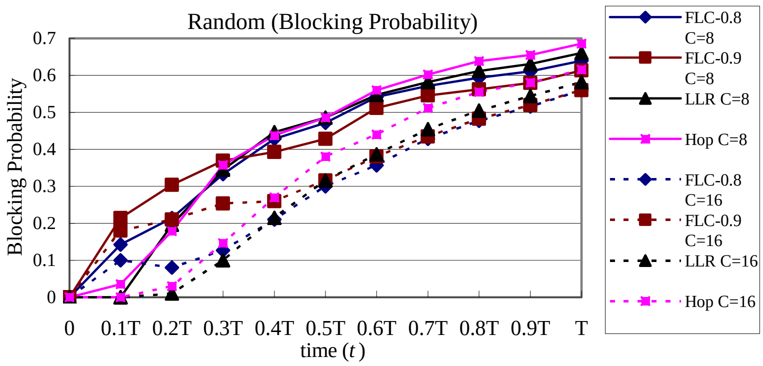

Fig. 5. Connections for FLC LLR, LLR, and Hop by Hop algorithm with first-fit wavelength assignment.

### 3.2 Blocking Probability

Figs. 6 (a) and (b) show the blocking probabilities for three routing algorithms with the first fit and the random wavelength assignment algorithms. The Hop by Hop algorithm has lower blocking probability when the saturation time is less than 0.3T. In Fig. 6 (a), the simulation shows that the LLR algorithm performs better than the FLC LLR algorithm when the saturation time is below 0.4T. The possible reason is that the FLC LLR algorithm rejects the connection when the hop count is high and the value after defuzzification is smaller than the fuzzy limit. Another reason is that the unexpected traffic load generated by the LLR algorithm is tolerable when the saturation time is less than 0.4T. But, the side effect of the unexpected traffic load generated by the LLR algorithm comes up when the traffic is high. When the fuzzy limit is 0.9, the number of channels is 8 and the saturation time is 0.9T, the FLC LLR algorithm reduces by 5% the blocking probability compared with the LLR algorithm. On the other hand, when the fuzzy limit is 0.8, the number of channels is 16 and the saturation time is 0.9T, the FLC LLR algorithm reduces by 5% the blocking probability compared with the LLR algorithm. The same simulation result for the random wavelength assignment algorithm is shown in Fig. 6 (b).




(a)

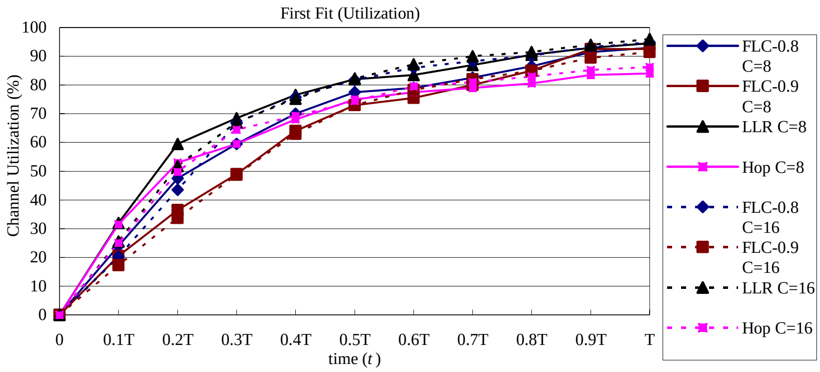



(b)

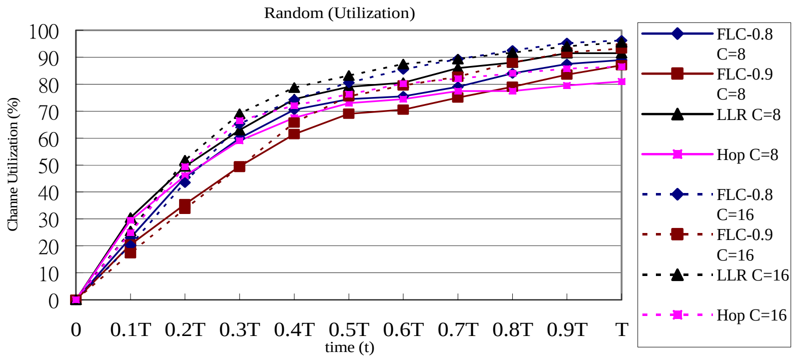
Fig. 6. Blocking probabilities for FLC LLR, LLR, and Hop by Hop algorithm with the first fit wavelength assignment.

### 3.3 Channel Utilization

Figs. 7 (a) and (b) compare the channel utilizations for the three routing algorithms with two wavelength assignment algorithms, first-fit and random when the number of channels is 8 or 16. The simulation results show that when the saturation time is 0.2T, the channel utilization with the FLC LLR algorithm is 10% less than that with the LLC algorithm. Thus the FLC LLR algorithm properly selects a suitable lightpath that reduces the unexpected traffic load and increases the number of successful connections.




(a)




(b)

Fig. 7. Channel utilizations for FLC LLR, LLR, and Hop by Hop algorithm with the first fit wavelength assignment.

### 3.4 Blocking Probability with and without Wavelength Converters

Fig. 8 shows the blocking probabilities for three routing algorithms, FLC LLR, LLR, and Hop by Hop algorithm with and without wavelength converters using the first fit wavelength algorithm. The blocking probabilities are improved when the converters are used for the three routing algorithms, and our proposed FLC LLR algorithms with and without the converter have lower blocking probability when the saturation time is less than 0.3T.

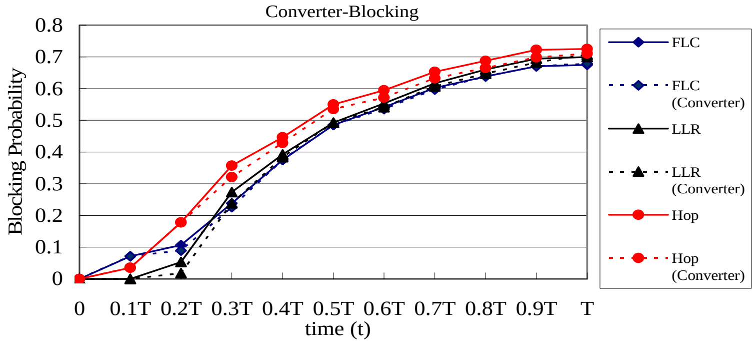



Fig. 8. Blocking probabilities for FLC LLR, LLR and Hop by Hop algorithm with wavelength converter using first fit wavelength assignment.

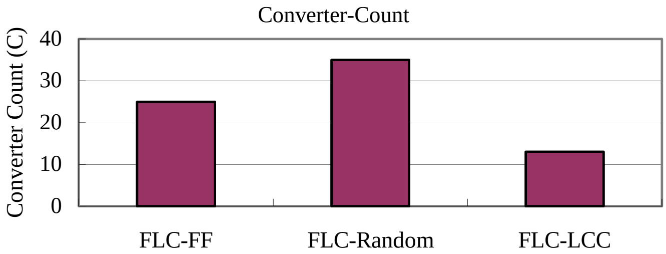



Fig. 9. Average number of conversions needed for first fit, random and least converter count wavelength assignment algorithms embedded in the FLC LLR when the saturation time is 0.7T.

### 3.5 Number of Conversions Needed with Wavelength Converters

The advantage of the DWDM network with wavelength converters is that the wavelength continuity constraint can be ignored. But, the cost of the wavelength converter and delay time of the number of conversions need to be considered to enhance the system performance. Fig. 9 shows the average number of conversions needed for first fit (FLC-FF), random (FLC-Random) and least converter count (FLC-LCC) wavelength assignment algorithms embedded in FLC LLR. The simulation shows that the FLC-LCC outperforms the FLC-Random and better than the FLC-FF when the saturation time is 0.7T.

## 4. CONCLUSIONS

This paper proposed the dynamic fuzzy logic control (FLC) LLR algorithm to balance the traffic load of each link and minimize the hop count for each path in WDM mesh networks. Due to unexpected traffic load with the LLR algorithm is generated when the length of lightpath is long and the traffic load is heavy, the fuzzy logic control based on traffic load and length of lightpath is used to determine whether the connections can be established. The simulation results show that the FLC LLR algorithm provides both fair and flexible lightpath connections to the WDM network. The algorithm without converters using appropriate fuzzy limit has better system performance than the LLR algorithm in terms of connections, blocking probability and channel utilization when saturation time is more than 0.5T. Compared with the number of connections and channel utilization, the FLC LLR algorithm properly selects a suitable lightpath that reduces the unexpected traffic load and increases the number of successful connections. Furthermore, the simulation shows that FLC-LCC outperforms the FLC-Random and better than the FLC-FF when three RWA algorithms with converters are considered. The proposed algorithm can be further applied to different topologies in the future.

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