Abstract— It has been demonstrated that advertising the availability of wavelength and converter resources in all-optical DWDM transport networks with sparse wavelength conversion capabilities can drastically improve the blocking performance of these networks thus achieving better usage of the network resources. An important aspect with consequences in network performance is when to originate the wavelength-availability and converter-availability Link State Advertisements (LSAs). Frequent link-state advertisements could overwhelm the network control plane with many update messages that need to be processed. On the other hand, delaying these advertisements could result in inaccurate link-state information thus degrading the network blocking performance. In this paper, we propose two different link-state update policies to advertise the availability of wavelength and converter resource in all-optical DWDM transport networks with sparse wavelength conversion capabilities. The first one is very simple and serves as our base policy for comparison. The second policy, which is very efficient in handling the dynamic nature of all-optical DWDM networks with different degrees of wavelength conversion, reduces the number of LSAs considerably while maintaining the call blocking probability.

Keywords—Link-State routing; fuzzy logic; DWDM; wavelength conversion; OSPF; all-optical networks; LSA

I. INTRODUCTION

Current advances in optical device technologies have enabled these devices to perform their functionality in the optical domain (sometimes referred to as Optical-Optical-Optical or O-O-O) without the need for O-E-O (Optical-Electrical-Optical) conversion. Optical switches, optical filters, optical amplifiers, DWDM multiplexers, and tunable lasers that perform their functionality in the optical domain form the cornerstone that is enabling all-optical DWDM networks. These all-optical DWDM networks [8][9] are expected to offer an attractive and cost effective solution to handle the unprecedented demands for more capacity facing the telecommunications industry.

Routing protocols are required to operate on the control plane of all-optical DWDM networks in order to distribute Quality of Service (QoS) parameters that can help the signaling protocols [5] (e.g., OIF and GMPLS) to establish the required lightpaths over the optical network without performing lots of crankbacks. The Open Shortest Path First (OSPF) protocol is an efficient and commonly used link-state routing protocol that can be employed to distribute QoS parameters through the optical network utilizing its flooding mechanism. In [2], we proposed a new opaque LSAs to advertise the availability of wavelength and converter resources in all-optical DWDM transport networks with sparse wavelength conversion capabilities and demonstrated that this can drastically improve the blocking performance of these networks thus achieving better usage of the network resources. However, the issue of when to advertise these LSAs has not been addressed yet, a very important issue in these networks given the rapid changing nature in the availability of these resources.

In this paper, we propose two different origination policies to advertise the wavelength and converter availability LSAs presented in [2]. The first one is very simple and serves as our base policy for comparison. The second policy is very efficient in handling the dynamic nature of all-optical DWDM networks with different degrees of wavelength conversion. The rest of this paper is organized as follows: Section II provides an overview of the link-state update policies presented in the literature. Sections III and IV present our proposed Immediate and Fuzzy Link-State Update Policies, respectively. Section V provides performance results comparing these policies and Section VI presents our conclusions.

II. RELATED WORK

A number of heuristic algorithms have been proposed to provide Quality of Service (QoS) routing based on multiple parameters [1]. However, recent studies conducted on IP-based networks concluded that QoS routing uses complex and frequent computations and generates a high volume of routing protocol overhead compared to routing that is not sensitive to QoS parameters [3].

Several link-state update policies have been proposed in the literature to minimize the routing protocol overhead needed to exchange the QoS parameters needed for QoS routing. A link-
state update policy determines when a node should originate link state update messages and the contents of these updates. Apostolopoulos et al. [3][4] classified the mechanisms used to trigger the link state update messages as follows:

- **Threshold based triggers**: A link-state update message is originated whenever the difference between the current and previously advertised link state is above a certain threshold, e.g., when the difference is above 70%.

- **Class based triggers**: A link-state update message is originated whenever the value of a certain parameter crosses a class boundary, e.g., when the packet delay belongs to a class that is different from the one that it belonged to at the time of the previous update.

- **Timer based triggers**: A link-state update message is originated at fixed intervals.

The trade-off between these mechanisms is between the volume of link state update messages and the accuracy of the state information available to the route computation engine. The exchange of the link state information at a higher rate results in more accurate state information provided to the route computation engine. This means that the route computation engine will be able to provide less call blocking probability at the expense of a large volume of link state traffic. Similarly, exchanging the link state information at a lower rate provides the route computation engine with less accurate information about the state of the network. This means that the route computation engine will encounter a higher degree of call blocking but at the same time the network control plane is not overwhelmed with large volume of link state updates. These techniques have been applied in IP-based networks [3].

In this paper, we propose two link-state update mechanisms. The first one, called Immediate Link-State Update Policy (IUP), is very simple and serves as our base policy for comparison. The second policy, called Fuzzy Link-State Update Policy (FUP), is very efficient in handling the dynamic nature of all-optical DWDM networks with different degrees of wavelength conversion. These mechanisms are presented next.

### III. IMMEDIATE LINK-STATE UPDATE POLICY (IUP)

Under this link-state update policy, each node should originate wavelength-availability and converter-availability Opaque LSAs whenever a new Router LSA is originated. Also, each node should originate a wavelength-availability opaque LSA for each of its outgoing links whenever the wavelength availability mask of the link is changed. Moreover, each link should originate a converter-availability LSA whenever the usage profile of the wavelength conversion resources installed on the switch are changed. Figure 1 depicts this simple origination mechanism that advertises wavelengths and converters availability LSAs as soon as the availability profiles of these resources change. We call this policy the **Immediate Link-State Update Policy (IUP)**.

The strength of this policy stems from its simplicity and it can be used in long-haul DWDM all-optical networks where lightpath requests are static and do not change frequently. However, in networks with dynamic lightpath requests, this policy can result in a large volume of link state updates since the availability of the wavelength and conversion resources is constantly changing. This is the case of metro-edge and metro-core all-optical DWDM networks for which the Immediate Link-State Update Policy presented in this section might not be the best solution. The following section presents a fuzzy logic-based link-state update mechanism that can efficiently handle networks with dynamic lightpath requests, as it is the case in most metro-edge and metro-core all-optical networks.

```plaintext
if (One of the neighboring routers changes to/from the FULL state) then Originate a new Router LSA

if (LS-age field of one of the router’s self-originated advertisements > LSRefreshTime) then Originate a new instance of the LSA that just expired

if (wavelength availability on one or more of the outgoing links changed) then Originate new wavelength availability opaque LSA
```

Figure 1. The Immediate Link-State Update Policy

### IV. FUZZY LINK-STATE UPDATE POLICY (FUP)

Since the availability of wavelength and wavelength-conversion resources in metro-edge and metro-core environments change very frequently, a smart link-state update policy that minimizes the exchange of link state information while not hindering the blocking probability is needed. In order to satisfy this requirement, in this section we introduce the Fuzzy Logic-based Link-State Update Policy (FUP).

#### A. Fuzzy Inference System

Our fuzzy-based link-state update policy is based on two simple rules as shown in Figure 2. The first rule causes the link state information to be exchanged less often when the wavelength and wavelength-conversion resources installed in the network are tightly utilized. On the other hand, the second rule causes the link state information to be exchanged more often when the wavelength or wavelength-conversion resources installed in the network are highly utilized.

The rationale behind these rules is very simple. In the first case, inaccuracies in the state information pertaining to the availability of the wavelength and wavelength-conversion

...
resources in the network don’t increase the call blocking probability because old information related to resources not utilized is still valid. In the second case, the network becomes more utilized, and therefore most of its resources experienced changes since the last update, augmenting the error in the state information. Therefore, in order to avoid increasing the call blocking probability unnecessarily, state information must be advertised more frequently. The net effect of our policy is the reduction of the volume of state information exchanged while not increasing the call blocking probability.

The fuzzy interference system presented in Figure 2 is based on the linguistic approach that depends on linguistic variables whose values are words or sentences in a natural or artificial language rather than numbers. Our fuzzy link-state update policy utilizes human expert experience to identify when the network resources in terms of wavelengths and converters are considered to be highly utilized or lightly utilized. However, since the imprecision or fuzziness is inherent in human judgments, representing the utilization of the different resources using linguistic variables makes it easier and more flexible for the human operator to specify the level of usage of the different network resources. Then, a fuzzy-inference rule base can be used to aggregate the network resource utilizations in terms of wavelength and converter resources into a single value that specify the waiting factor to send the next link-state update message. The waiting factor calculated using the fuzzy-inference rule base is an absolute number. This number should be multiplied by the average call inter-arrival time to calculate the actual waiting time between two consecutive link-state updates. No link-state update messages needs to be originated when the waiting timer expires before having a new link-state update, i.e., no need to originate new link-state update messages if the availability of the wavelength and converter resource did not change.

In addition to performance, the fuzzy link-state update policy presented in this section has other advantages. First, it can be easily extended or modified since it is based on common sentences (rules). Using mathematical functions to represent these rules might be a very difficult task. Furthermore, even if it is feasible to do that, it is definitely not easy to modify them. Second, even though the link-state update policy presented here applies to all-optical DWDM networks with sparse wavelength conversion capabilities, a similar approach can be used to design a fuzzy-inference rule base that applies to IP-based networks to advertise QoS parameters.

### B. Membership Functions

In our fuzzy link-state update policy, membership functions are used in the antecedents and consequents of rules. In fuzzy logic engineering applications, the most commonly used membership functions are piecewise linear, triangular, trapezoidal, s-functions, z-functions, and Gaussian [7]. These membership functions have simple formulas, are computationally efficient and have been extensively tested in real world applications with real-time requirements. The proposed model utilizes two linguistic variables to represent the availability of wavelength and converter resources in the optical network and one output linguistic variable to represent the waiting factor between two consecutive link-state updates.

The membership functions assigned to these variables are chosen as s-functions and z-functions for the input linguistic variables, and Gaussian functions for the output variable. The s and z membership functions are chosen for the input variables because they can be configured to provide fast as well as slow transitions from membership to non-membership and vice versa, e.g., from high-degree of utilization to a low-degree or utilization. The Gaussian membership function is chosen for the output variable because it results in smooth switching as the input linguistic variables change values. It is worth mentioning here that the studies conducted on fuzzy systems have shown that the choice of membership functions does not drastically change the behavior of the system.

### if (Bandwidth Utilization is low) and (Converter Utilization is low)

then Update Frequency is slow

### if (Bandwidth Utilization is high) or (Converter Utilization is high)

then Update Frequency is fast

![Figure 2. Fuzzy rule base of the proposed link-state update policy](image)

The s and z membership functions are specified by two parameters \(X_l\) and \(X_r\) and the Gaussian membership function is specified by two parameters \(c\) and \(\sigma\) as follows:

\[
s(x_l, x_r, x) = \begin{cases} 
1, & x < x_l \\
1 + \frac{1}{2} \cos \left( \frac{x - x_r}{x_r - x_l} \pi \right), & x_l \leq x \leq x_r \\
0, & x > x_r 
\end{cases}
\]

\[
z(x_l, x_r, x) = \begin{cases} 
0, & x < x_l \\
1 + \frac{1}{2} \cos \left( \frac{x - x_r}{x_r - x_l} \pi \right), & x_l \leq x \leq x_r \\
1, & x > x_r 
\end{cases}
\]

\[
gaussian(c, \sigma, x) = e^{-\frac{(x-c)^2}{2\sigma^2}}
\]

Figure 3 shows the general form of a network resource availability membership function. Low membership function provides different degrees of membership that ranges from full membership when the resource utilization is lower than 10% to non-membership when the resource utilization exceeds 70%. On the other hand, High membership functions provides different degrees of membership that ranges from non-membership when the resource utilization is lower than 30% to full membership when the resource utilization exceeds 90%. A human operator can easily tune the parameters involved in these membership functions.
Figure 4 shows the general form of the waiting factor output membership functions. Low waiting factor means that the waiting time between two consecutive link-state originations is small resulting in more frequent updates. High waiting factor, on the other hand, means that the waiting time between the link-state updates is longer resulting in less frequent exchange of link-state update messages on the network control plane. The output membership functions have the following parameters:

Low Waiting Factor: \text{gaussian}(0, 1.5, x) \\
High Waiting Factor: \text{gaussian}(10, 1.5, x)

Figure 5 provides an example that illustrates the computation of the update interval based on the fuzzy rule base. The recommended rules try to maximize the waiting factor as long as the wavelength and converter resources in the network are not highly utilized. Higher resource utilizations result in lower waiting factors. The waiting factor increases gradually as the resource utilizations increase. This helps in minimizing the link-state update messages exchange on the optical network control plane whenever that is possible. It is worth noticing that our policy utilizes the min, max, min, max, and centroid methods for the fuzzy and, or, implication, aggregation and defuzzification operators, respectively.

V. PERFORMANCE RESULTS

We carried out a performance study of the IUP and FUP policies presented above. Figures 6 and 7 plot the average number of update messages and the time between the messages exchanged under different traffic loads. The figure shows that the average number of messages exchanged using our FUP policy is considerably smaller than the one needed by the IUP LSA origination policy. In addition, in Figure 8 we compare the blocking probability of both schemes under different traffic loads and show that the FUP policy doesn’t increase the blocking probability. Based on these findings, we conclude that our fuzzy-based LSA origination policy enables the routing protocol to exchange less update messages without hindering the call blocking performance (see Figure 11).
VI. CONCLUSION

In this paper, we propose two link-state origination policies to advertise wavelength and converter resources in all-optical DWDM networks. The Immediate Link-State Update Policy provides a simple solution for long-haul and metro-core networks where resource availabilities do not change frequently. For optical networks with dynamic traffic demands, our Fuzzy Link-State Update Policy provides an elegant alternative that minimizes the exchange of link-state update messages on the network control plane without hindering the network blocking performance.

REFERENCES


