Routing Framework for All-Optical DWDM Metro-Core and Long-Haul Networks with Sparse Wavelength Conversion Capabilities

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ABSTRACT

Next generation IP over optical networks are gaining a lot of attention due to their savings potential and support of foreseen applications and bandwidth demands. However, many new protocols and mechanisms have been introduced at a very fast pace and they still need to be evaluated, refined and sometimes re-invented. In this paper, we propose an entire routing solution that supports optical switches with limited wavelength conversion capabilities suitable for wide area as well as metropolitan area networks. First, we propose two new LSAs to the standard OSPF protocol that will advertise the availability of wavelengths and converters per switch. A fuzzy logic algorithm is proposed to reduce the amount of advertisements due to the rapidly changing nature of these variables without increasing the blocking probability. Then, a fuzzy logic-based new Routing and Wavelength Assignment computation engine is introduced that outperforms current schemes in terms of blocking probability and average path cost.

1. Introduction

Traditional telecom transport networks are comprised of overlays of SONET ADM (Add and Drop Multiplexers) and DCS (Digital Cross-connect Systems) equipment for traffic grooming. Such networks, shown in Figure 1, suffer from key scalability and cost problems particularly because DCSs are expensive (on a per port basis), occupy large footprints (multiple bays), consume high power, and are managed by standalone management systems.

The traditional approach that has been used over the years by telecom service providers to upgrade these networks involves the deployment of additional DCS and ADM systems. 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, 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 are expected to offer an attractive and cost effective solution to upgrade telecom transport networks to handle the demands for more capacity.

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Figure 1(b) illustrates this approach to upgrade current transport networks. This approach introduces a new photonic layer that is composed of Optical Cross-connect Systems (OXCs) or Optical Transport Systems (OTSS) that perform their functionality in the optical domain. These systems perform their switching functionality at the wavelength level freeing DCS and ADM equipment and leaving them to handle sub OC-48 traffic switching and grooming enabling them to perform the functionality that they were designed for in the first place.

While all-optical DWDM transport networks offer capacities above those offered by traditional electro-optical networks, several challenges are introduced beyond those known in traditional electro-optical networks. For instance, wavelength converters are expensive and sparse wavelength conversion has been shown to provide similar performance to that of full conversion. Routing protocols for all-optical DWDM networks don’t convey information about the usage of the wavelength converters. Furthermore, including this type of information is critical because of its importance in making intelligent routing decisions. Finally, Routing and Wavelength Assignment (RWA) algorithms must be modified to consider this new variable in the computation thus optimizing this resource. In this work, we consider all these issues providing a framework to handle routing in DWDM networks with limited wavelength conversion capability.

The remainder of this paper is organized as follows. Section 2 provides an introduction to the RWA problem in all-optical DWDM networks with and without the lambda continuity constraint. Section 3 provides an Integer Linear Programming (ILP) formulation for the routing problem faced in DWDM networks with limited wavelength conversion capabilities. Section 4 presents an extension to the OSPF routing protocol to handle routing in all-optical DWDM networks regardless of capabilities in terms of wavelength conversion. Section 5 introduces a fuzzy based heuristic to implement a route computation engine that can be used to efficiently route lightpaths in the optical networks given any wavelength conversion constraints that might exist at each node. Simulation results are presented in this section to compare our proposed heuristic with other approaches used in the literature. Finally, Section 6 discusses our findings and future extension to this work.

2. RWA with Limited Wavelength Conversion Capabilities

One of the most important goals in this new IP over optical paradigm is the support of real-time provisioning. Currently, service providers have to go through a lengthy and tedious process in order to satisfy a client's request. The realization of this vision however, depends on many factors. In an IP over DWDM network, given a request for an optical channel, a Routing and Wavelength Assignment (RWA) problem must be solved so that a path and a wavelength or lambda is assigned to each request from source to destination. In the absence of wavelength converters, a lightpath must be established from source to destination using the same wavelength or lambda; this is a wavelength constraint network. On the other hand, with wavelength converters lightpaths can be made of different lambdas, leading to an expected lower call blocking probability. There are also different types of request scenarios, commonly static and dynamic requests. With
static requests, users' demands are known in advance and the provisioning problem is to set up lightpaths to satisfy all the requests while minimizing the amount of network resources, such as the number of lambdas. In this case, the RWA problem is known as the Static Lightpath Establishment (SLE) problem. With dynamic requests, connections are requested in a dynamic fashion and the RWA problem will try to establish lightpaths for them while minimizing the blocking probability. This is known as the Dynamic Lightpath Establishment (DLE) problem.

The DLE needs the support of a routing protocol and a routing engine to disseminate resource information and solve the RWA problem. In IP over optical networks, the Generalized MPLS framework suggests the use of existing IP protocols for routing and signaling with appropriate enhancements [GMPLS]. Extensions to the link state routing protocol Open Shortest Path First (OSPF) [OSPFE] disseminate network resource availability by means of Link State Advertisements (LSA) that switches send periodically. Network information is then used by a constraint-based path computation algorithm to compute routes subject to pre-defined constraints. Once the entire route is known, a signaling protocol is invoked to setup the connection. Constraint-based routing label distribution protocol (CR-LDP) [CRLDP] and resource reservation protocol with traffic engineering extensions (RSVP-TE) [RSVPTE] are the two most important signaling protocols. In this paper, we are concerned about OSPF and its support for networks with limited wavelength conversion capabilities.

The RWA problem as its name implies, consists of a routing and a wavelength assignment problem. For the routing subproblem, three main approaches are known: fixed routing, adaptive routing and semi-adaptive routing [CHAN94] [HARA97] [MOKH98] [RAMA98] [ZANG01]. For the wavelength assignment, several heuristics have been proposed such as First-Fit, MAX-SUM, Least Loaded, Most-Used, Relative Capacity Loss, Distributed Relative Capacity Loss, and many others. For a complete survey of the RWA, the reader can refer to [ZANG01]. In addition, Total Cost-Based Selection, Balanced Cost-Based Selection and Future Cost-Based Selection are more recent heuristics presented in [ASSI01] that solve both problems in an integrated manner.

Optical switches can be of two different types according to the conversion capabilities. Full wavelength conversion switches are those that can convert an incoming wavelength to any outgoing wavelength and in addition, the number of converters is equal to the total number of outgoing wavelengths. On the other hand, partial wavelength conversion switches are equipped with an optimal number of wavelength converters to minimize the high cost of these devices. Several studies have already considered the case of networks with wavelength converters. For example, [XIAO99][LEEK93][SUBR99] consider the case of optimal converter placement where the switches have full or limited conversion capabilities. Lately, it has been shown that the RWA and switch placement problems, which are usually solved separately, should be considered in an integrated manner [LIB03]. In this work we assume that the wavelength converters can convert any incoming wavelength to any outgoing one and that switches have a limited number of converters. It has been shown that networks with limited conversion capabilities can achieve similar blocking probability in a more cost effective manner [XIAO99].
In this work we present a complete framework for routing in all-optical networks with limited wavelength conversion capabilities. First, we present an Integer Linear Programming (ILP) formulation to solve the RWA problem assuming limited wavelength conversion under the scenario of static requests or Static Lightpath Establishment (SLE). Then, we propose an extension to the OSPF protocol to advertise the wavelength and converter resources, an adaptive flooding protocol based on fuzzy logic that minimizes the routing protocol advertisements while not affecting the blocking probability. Finally, an adaptive route computation engine that is also based on fuzzy logic is introduced that solves the RWA problem assuming limited wavelength conversion under the scenario of dynamic requests or Dynamic Lightpath Establishment (DLE). We compare our solution against First Fit with dynamic routing, as it has been shown to be very simple to implement while providing acceptable performance [ZHUY00].

It should be noticed here that the Routing and Wavelength Assignment in all-optical networks with Limited Wavelength Conversion Capabilities (RWA-LWC) is a generalization of the RWA problem that holds for networks with the wavelength continuity constraint as well as networks that posses more wavelength conversion capabilities. Figures 2(a) and 2(b) provide a simple illustration of the RWA problem with the wavelength continuity constraint and when the network has a limited number of wavelength converters.

3. ILP Formulation for the RWA-LWC Problem

The RWA-LWC problem can be formulated as an Integer Linear Programming (ILP) problem in which the objective function is to minimize the total cost of all lightpaths that need to be established in the optical network. Let us define the following:

- **N**: Number of switches.
- **E**: Number of links.
- **W**: Number of wavelengths per link.
- **T**: Total number of lightpaths that need to be established.
- **Π**: Number of source-destination pairs.
Figure 1: (a) Conventional transport networks: Each signal is terminated at each B-DCS and ADM node. (b) Future transport systems with all-optical OTS systems, the released capacity on the B-DCS and ADM nodes can be used to extend the life of the network.

Figure 2: (a) Illustrates the RWA problem with no wavelength conversion. (b) Illustrates the RWA problem with LWC.
\( Q = \{ q_i \}, i = 1,2,\ldots, \Pi \): Vector of size \( \Pi \), where element \( q_i \) represents the number of requested lightpaths between the \( i^{th} \) source-destination.

\( R = \{ r_i \}, i = 1,2,\ldots, \Pi \): Vector of size \( \Pi \), where element \( r_i \) represents the number of all possible paths between the \( i^{th} \) source-destination pair.

\( V = \{ v_i \}, i = 1,2,\ldots, N \): Vector of size \( N \), where element \( v_i \) represents the number of wavelength converters installed on the \( i^{th} \) node.

\( P^i = \{ p^i_j \}, j = 1,2,\ldots, r_i \): A list of \( \Pi \) vectors that represent the paths on which each of the source-destination pairs can be routed, \( P^i \) is the \( i^{th} \) vector of the list. Element \( p^i_j \) represents the \( j^{th} \) path on which the \( i^{th} \) source-destination pair can be routed. These paths can be enumerated using the \( k \)-shortest paths algorithm. Notice that two paths are considered to be distinct if they go through different fibers or different wavelengths in their route from source to destination.

\( U^i = (u^i_{j,k}), j = 1,2,\ldots, r_i, k = 1,2,\ldots, E \): A list of \( \Pi \) vectors that represent the usage of the link resources by the different paths, vector \( U^i \) is the \( i^{th} \) vector of the list. Element \( u^i_{j,k} = 1 \) if the \( j^{th} \) path between the \( i^{th} \) source-destination pair uses link \( k \), otherwise \( u^i_{j,k} = 0 \).

\( X^i = (x^i_{j,k}), j = 1,2,\ldots, r_i, k = 1,2,\ldots, N \): A list of \( \Pi \) vectors that represent the usage of the wavelength conversion resources by the different paths, vector \( X^i \) is the \( i^{th} \) vector of the list. Element \( x^i_{j,k} = 1 \) if the \( j^{th} \) path between the \( i^{th} \) source-destination pair uses a wavelength converter that is installed on node \( k \), otherwise \( x^i_{j,k} = 0 \).

\( Y^i = (y^i_j), j = 1,2,\ldots, r_i \): A list of \( \Pi \) vectors that represent the cost of the different paths, vector \( Y^i \) is the \( i^{th} \) vector of the list. Element \( y^i_j \) is the cost of the \( j^{th} \) path between the \( i^{th} \) source-destination pair.

\( Z^i = (z^i_{j,k}), j = 1,2,\ldots, r_i, k = 1,2,\ldots, E \* W \): A list of \( \Pi \) vectors that represent the usage of the wavelength resources (lambda) by the different paths, vector \( Z^i \) is the \( i^{th} \) vector of the list. Element \( z^i_{j,k} = 1 \) if the \( j^{th} \) path between the \( i^{th} \) source-destination pair uses wavelength \( \lfloor \frac{k}{E} \rfloor + 1 \) on link \( \lfloor \frac{k}{W} \rfloor \), otherwise \( z^i_{j,k} = 0 \).

\( S^i = (s^i_j), j = 1,2,\ldots, r_i \): A list of \( \Pi \) vectors that represent the cost of the different paths, vector \( S^i \) is the \( i^{th} \) vector of the list. Element \( s^i_j = 1 \) if the \( j^{th} \) path between the \( i^{th} \) source-destination pair is selected, otherwise \( s^i_j = 0 \).
The objective function of the RWA-LWC problem is to minimize the total cost of all requested lightpaths. The RWA-LWC problem is then formulated as follows:

\[
\text{Minimize } \sum_{i=1}^{\Pi} (Y^i)^T S^i
\]

Subject to the following constraints:

\[
S^i_j \leq 1 \quad \forall \quad 1 \leq i \leq \Pi \quad 1 \leq j \leq r_i \quad (1)
\]

\[
Q^i \leq \sum_{j=1}^{r_i} S^i_j \quad \forall \quad 1 \leq i \leq \Pi \quad (2)
\]

\[
(S^i)^T U^i \leq W \quad \forall \quad 1 \leq i \leq \Pi \quad (3)
\]

\[
(S^i)^T X^i \leq V^i \quad \forall \quad 1 \leq i \leq \Pi \quad (4)
\]

\[
(S^i)^T Z^i \leq 1 \quad \forall \quad 1 \leq i \leq \Pi \quad (5)
\]

In this formulation, the symbol $T$ indicates the transpose operation. Equation (1) indicated that a path can be selected or not selected (binary variable). Equation (2) indicates that all the requested lightpaths need to be established for a solution to be feasible. Equation (3) verifies that no more than $W$ wavelengths are used on a single link. Equation (4) verifies that the wavelength conversion capability constraints are respected. Finally, Equation (5), guarantees that no more than one connection is carried on any given wavelength of all links in the network.

Table 1 shows two scenarios to which we applied the ILP formulation presented above. Table 1 also indicates the optimal resources that need to be allocated to each lightpath. Figure 3 shows the topology of the network on which the lightpaths indicated in Table 1 need to be established. In this example, each wavelength converter is assumed to have a cost of 100. We implemented the $k$-shortest paths algorithm to enumerate the different paths for the ILP formulation then we used CPLEX to solve the formulation. It should be noted here that as the size of the network and the number of supported wavelengths grow, the formulation presented in this section becomes of limited use. In Section 5, we present a heuristic that is based on fuzzy logic to handle such networks.
C : Number of wavelength converters installed on the node
Number of wavelengths = 3 (per each bi-directional link)

Figure 3: Sample network with LWC capabilities.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Source→Destination</th>
<th>Route</th>
<th>Wavelengths</th>
<th>Converters</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A → F</td>
<td>AB → BD → DF</td>
<td>3 3 3</td>
<td>0 0</td>
</tr>
<tr>
<td>A → F</td>
<td>AC → CE → EF</td>
<td>1 1 1</td>
<td>3 3 3</td>
<td>0 0</td>
</tr>
<tr>
<td>E → A</td>
<td>EC → CA</td>
<td>2 2 2</td>
<td>1 0</td>
<td></td>
</tr>
<tr>
<td>E → A</td>
<td>EC → CA</td>
<td>2 2 2</td>
<td>2 2 2</td>
<td>0</td>
</tr>
<tr>
<td>E → B</td>
<td>ED → DB</td>
<td>3 3 3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>C → D</td>
<td>CB → BD</td>
<td>1 1 1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>E → A</td>
<td>EC → CA</td>
<td>3 3 3</td>
<td>0</td>
</tr>
<tr>
<td>E → B</td>
<td>ED → DB</td>
<td>1 1 1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>E → B</td>
<td>ED → DB</td>
<td>2 2 2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>E → B</td>
<td>EC → CB</td>
<td>3 3 3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>E → B</td>
<td>EC → CB</td>
<td>1 1 1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>A → B</td>
<td>AB</td>
<td>3 3 3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>A → B</td>
<td>AB</td>
<td>2 2 2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>A → B</td>
<td>AB</td>
<td>1 1 1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>A → B</td>
<td>AC → CB</td>
<td>1 3 3</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Examples of route, wavelength, and converter assignment in LWC networks.
4. OSPF routing extension

As explained previously, a requested optical lightpath needs to be assigned a route and a set of wavelengths throughout the optical network domain from source to destination. A routing protocol is required to disseminate wavelengths’ and converters’ availability within the optical network domain. K. Kompella and Y. Rekhter presented an Internet draft [KOMP02a] in which they discussed the information that needs to be flooded by any routing protocol in support of GMPLS. In that draft, a generic approach to handle networks comprised of PSC (Packet Switch Capable), TDMC (Time Division Multiplexing Capable), LSC (Lambda Switch Capable), and FSC (Fiber Switch Capable) equipment was presented, but the draft did not address routing in networks comprised of LSC switches with limited number of wavelength converters.

It should be emphasized here that [KOMP02a] is designed to handle a network comprised of PSC, TDMC, LSC, and FSC equipment. We think this approach; even though it is generic; complicates the routing protocol and makes it inefficient since the routing protocol should handle the advertisements of equipment employing all previously mentioned switching technologies even though such equipment might belong to different overlays. Instead, in this work, we take the stand that telecom networks employ overlay architecture and it is more efficient and feasible to design a routing protocol that is specific to each of the employed overlays. In this case, despite that each overlay would employ its own routing protocol, each overlay would be able to advertise more information that is specific to that overlay resulting in more efficient routing and better provisioning of network resources. In this section, we present an extension to the OSPF protocol that addresses the routing problem faced in all-optical DWDM networks with limited wavelength conversion resources. Even though the routing extension presented in this paper is an overlay specific one that pertains to all-optical DWDM networks (Photonic overlay in Figure 1b) regardless of their wavelength conversion capabilities, a similar approach can be adapted to design routing protocols for other overlays.

Our proposed routing extension is based on three major changes to the OSPF routing protocol. The first change consists of the introduction of two new Link State Advertisements (LSAs), the second change involves modifications to the flooding policy of the protocol, and the last change involves modifications to the route computation component used in the original OSPF protocol. The following two subsections address the first two changes while Section 5 addresses the changes to the route computation engine.

4.1. New Link State Advertisements description

The purpose of the introduced LSAs is to advertise the number of available wavelengths per fiber and the number of wavelength conversion resources available within a switch. Our extension is generic and it can handle the all-optical DWDM networks composed of LSC switches regardless of their wavelength conversion capabilities. The introduced LSAs use the OSPF opaque LSA option as a vehicle to advertising these parameters.
Figure 4(a): Opaque LSA header information.

Figure 4(b): Opaque LSA structure.
<table>
<thead>
<tr>
<th>LS Age</th>
<th>Option</th>
<th>LS Type=10</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE Type</td>
<td>TE LSA ID</td>
<td>LSA#</td>
</tr>
<tr>
<td></td>
<td>Advertising Router</td>
<td></td>
</tr>
<tr>
<td>LS Sequence Number</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS checksum</td>
<td>Length=108</td>
<td></td>
</tr>
<tr>
<td>Type=2</td>
<td>Length=84</td>
<td></td>
</tr>
<tr>
<td>Type=2</td>
<td>Length=4</td>
<td></td>
</tr>
</tbody>
</table>

| Link ID | |
|---------| |
| Type=3 | Length=4 |

| Local Interface IP Address | |
|---------------------------| |
| Type=4 | Length=4 |

| Remote Interface IP Address | |
|-----------------------------| |
| Type=11 | Length=4 |

| Outgoing Interface Identifier | |
|-------------------------------| |
| Type=12 | Length=4 |

| Incoming Interface Identifier | |
|-------------------------------| |
| Type=32773 | Length=4 |

<table>
<thead>
<tr>
<th>Link Protocetion Type</th>
<th>Not Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type=32774</td>
<td>Length=8</td>
</tr>
</tbody>
</table>

| Shared Risk Link Group (SRLG1) | |
|-------------------------------| |
| Shared Risk Link Group (SRLG2) | |
| Type=32775 | Length=20 |

| Length of Mask | |
|----------------| |
| Bandwidth Mask | |
| Reserved for Future Use | |

Figure 4(c): Wavelength availability opaque LSA.

<table>
<thead>
<tr>
<th>LS Age</th>
<th>Option</th>
<th>LS Type=10</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE Type</td>
<td>TE LSA ID</td>
<td>LSA#</td>
</tr>
<tr>
<td></td>
<td>Advertising Router</td>
<td></td>
</tr>
<tr>
<td>LS Sequence Number</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS Checksum</td>
<td>Length=32</td>
<td></td>
</tr>
<tr>
<td>Type=2</td>
<td>Length=8</td>
<td></td>
</tr>
<tr>
<td>Type=32776</td>
<td>Length=4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of Converters</th>
<th>Number of Used converters</th>
</tr>
</thead>
</table>

Figure 4(d): Converter availability opaque LSA.
The OSPF Opaque LSA option defined in [COLT98] provides a generalized mechanism for the OSPF protocol to carry additional information. An Opaque LSA consists of a standard LSA header followed by 32 bit aligned application specific information field, which is divided into TLV tuples of Type, Length, and Value (See Figures 4a and 4b). The LSA header contains the following fields:

- **LS Age**: Time in seconds since the LSA was originated.
- **Options**: The optional capabilities supported by the described portion of the routing domain.
- **LSA Type**: This field is set to 10 describing an opaque LSA to be advertised inside a single area.
- **Link State ID**: In our case (point-to-point), this field is set to the source interface IP address.
- **Advertising Router**: The Router ID of the router that originated the LSA
- **LS Sequence Number**: Successive instances of an LSA are given successive LS sequence numbers.
- **LS Checksum**: The Fletcher checksum of the complete contents of the LSA excluding the LS age field.
- **Length**: This field represents the length in bytes of the whole LSA.

Figure 4(c) depicts the structure of the wavelength availability Opaque LSA. This LSA contains the following fields:

- **Type = 2**: The Link TLV describes a single link.
- **Link ID**: This field identifies the other end of the link. In our case (point-to-point), this is the Router ID of the neighbor. The Link ID sub-TLV is of Type = 2, and is four bytes in length.
- **Local Interface IP Address**: This field specifies the IP address of the interface corresponding to this link. The local interface IP address fields are used to discern multiple parallel links between systems. The type of the sub-TLV corresponding to this field is 3.
- **Remote Interface IP Address**: This field specifies the IP address of the neighbor's interface corresponding to this link. The remote interface IP address fields are used to discern multiple parallel links between systems. The type of the sub-TLV corresponding to this field is 4.
- **Outgoing Interface Identifier**: A link from Switch A to B may be assigned an outgoing interface identifier. This field represents a non-zero 32-bit number assigned by switch A. It should be unique within the scope of A. The type of the sub-TLV corresponding to this field is 11.
- **Incoming Interface Identifier**: A link from Switch A to B may be assigned an incoming interface identifier, which is the outgoing interface identifier from B's point of view. The type of the sub-TLV corresponding to this field is 12.
- **Type = 32773**: This is a new sub-TLV that we introduce to the OSPF protocol to represent the link protection type. The value of the link protection type can be from 1 to 6 to indicate the link protection type as explained in [KOMP02a].
- **Type = 32774**: This is a new sub-TLV that we introduce to the OSPF protocol to represent all the Shared Risk Link Groups (SRLGs) to which the link belongs. **Type =**
32775: This is a new sub-TLV that we introduce to the OSPF protocol to represent the usage profile of the wavelengths carried on the link described in this LSA.

- **Length of Mask**: Number of bits used to represent the bandwidth mask.
- **Bandwidth Mask**: This field represents the usage profile of all wavelengths on a specific link. This field is 120 bits long (can be extended or shortened as needed). If the value of the $i^{th}$ bit of this field is set to 1, then this indicate that the $i^{th}$ wavelength of the specified link is used. When the bit value is set to 0 this indicates that the wavelength is free and it can be assigned to an incoming lightpath.

Figure 4(d) depicts the structure of the converter availability Opaque LSA, where the number of converter field represents the total number of converters that are not used within the switch. This LSA contains the following fields:

- **Type = 32776**: We use the same concept used in defining the wavelength availability opaque LSA. We decide to assign a type value of 32776 to the converter availability sub-TLV.
- **Number of Converters**: The total number of converters installed on the switch.
- **Number of Used Converters**: The total number of converters currently in use on the switch.

It should be noted here that the sub-TLV introduced in our extension reside outside the interval [32768,32772], which is reserved for Cisco-specific extensions. We selected the range from 32773 to 32776 to represent the link protection type, Shared Risk Link Group (SRLG), wavelength availability, and converter availability sub-TLVs respectively.

4.2. Modified OSPF flooding policy

Since wavelengths’ and converters’ availabilities within the all-optical DWDM network domain can change very frequently, this raises the issue of “when” to advertise the changes in the network resources.

The original OSPF standard mandates a variety of tunable parameters controlling the flooding of LSAs, including the MinLSInterval timer that specifies the time between any two consecutive LSA originations. The main issue with the timer based flooding approach is that it is fixed and does not adapt to the state of the network. For example, setting the MinLSInterval timer to a value that is higher than needed results in an increased probability of call blocking and signaling crankbacks. Also, setting the timer to a value that is lower than needed results in a large number of unwanted updates that waste the processing power and the bandwidth of the network control plane.

Apostolopoulos et al. in [APOS98] presented a flooding policy based on computing the moving average to control the MinLSInterval timer to have it adapting to the network conditions. Here, we present a simple approach that employs fuzzy logic to design a flooding policy that adapts to the conditions of the all-optical DWDM networks in order to protect the control plane of the network from handling unwanted routing updates while not hindering the blocking probability.
The rule base used by our Fuzzy Inference System (FIS) to compute the value of the OSPF MinLSInterval timer is shown in Figure 5(a). The goal is to dynamically compute a timer value that is not very short to cause excessive updates but not very long to cause an increase in the call blocking probability. Rule 1 ensures that the computed timer value is short (causing faster protocol updates) whenever the utilization of the converter or wavelength resources is considered high. Rules 2 and 3 ensure that whenever the wavelength and converter resources on the switch are not highly utilized, then the computed timer value is longer (causing slower protocol updates). Different switches within the network can compute different values of the MinLSInterval timer causing each switch to send protocol updates based on the utilization of its resources. Figure 5(b) illustrates the membership functions employed in our model while Figure 5(c) provides an example that demonstrates the application of our fuzzy rule base to compute a value for the MinLSInterval timer. The computed value for the MinLSInterval timer is between 0 and 300 seconds. When the computed value is close to 0, protocol update messages will be sent almost instantaneously. But when the computed value is close to 300, the update messages will be sent on a slower basis. We selected that the maximum computed value of the MinLSInterval timer is 5 minutes assuming that exchanging update messages at this rate would not load the network control plane with unnecessary protocol update messages.

The performance of our proposed flooding policy has been compared with the instantaneous flooding approach. Figure 6(a) plots the average number of update messages exchanged under different traffic loads and shows that the average number of messages exchanged using our policy is less than that required by instantaneous flooding policies. Figure 6(b) plots the blocking probability under different traffic loads and shows that our policy doesn’t increase the blocking probability. Based on these findings, we can conclude that our flooding policy enables the routing protocol to exchange less update messages without hindering the probability of blocking.

5. Route computation module

Fuzzy logic has been successfully applied in the field of QoS routing in packet as well as circuit switched networks. Aboelela et al. [ABOE00] proposed a fuzzy logic based heuristic to solve the QoS routing problem in B-ISDN networks. Chemouil et al. [CHEM95] developed a fuzzy based routing system for circuit-switched networks and applied it to the French long distance telephone network. In this work, we apply fuzzy logic to routing in all-optical DWDM networks with limited wavelength conversion capabilities. In the proposed approach, a fuzzy-inference rule base is used to assign a fuzzy cost to each path based on crisp metrics that reflect the availability of resources within the network.

The proposed fuzzy-based model is shown in Figure 7. In this model, the k-shortest paths module is used to find the best possible routes for the requested lightpath. At the same time, the model monitors the availability of the wavelength and converter resources within the network domain by accessing the LSDB (Link State Database) that records the wavelength and converter LSAs described in the previous section. The wavelength assignment module employs a simple heuristic that we developed, we call this heuristic
the *most-continuous* wavelength assignment heuristic. In this heuristic, a set of wavelengths is assigned to the route in order to minimize the use of the wavelength converters. Our *most-continuous* wavelength assignment heuristic works by choosing the wavelength that is *most-continuous* (without wavelength conversion) and use wavelength conversion when the rest of the path cannot continue of the same wavelength (wavelength is used). The fuzzifier module takes these crisp inputs and generates fuzzy values that can be used by the fuzzy inference system. Next, the fuzzy inference system applies the rules available in its rule base to generate a fuzzy cost for each of the possible paths. Then, the defuzzifier module takes the fuzzy cost and generates a crisp cost for each of the possible paths. Finally, the path selection module compares the costs of all the possible paths and selects the best possible route.

Figure 8(a) summarizes the rule base used by our fuzzy inference system to compute a fuzzy cost for each of the possible routes generated by the k-shortest paths module. Rules 1 through 3 ensure that the fuzzy cost assigned to the path is very high in case the network does not have enough wavelength or converter resources, otherwise, the rules ensure that assigned fuzzy cost is very low. Rules 4 through 9 ensure that the actual cost of the path and the availability of link disjoint paths with respect to this path also play a vital role in assigning a fuzzy cost to the path. Figure 8(b) illustrates the membership functions employed in our routing model while Figure 8(c) provides an example that demonstrates the application of our fuzzy rule base to compute the path cost.

The performance of our proposed fuzzy-based routing heuristic has been compared with that of the shortest-path routing and first fit wavelength assignment approach. Figures 9(a) and 9(b) are based on a typical 20-node metro-core mesh network. The lightpath requests presented to the simulated network follow a Poisson arrival process (i.e. the inter-arrival times are exponentially distributed); the parameter of the arrival process depends on the traffic load that the simulated network is presented with. The call holding time utilized in this simulation is exponentially distributed with an average of 60 seconds. Figure 9(a) compares the blocking probability of our heuristic with that of the first fit approach. It is clear that our fuzzy approach outperforms the first fit approach. Figure 9(b) compares the average cost of the path selected by our heuristic with that selected by the first fit approach. Also here, it is clear that our fuzzy approach generates cheaper paths on average. Based on these findings, we can conclude that our fuzzy-based routing heuristic provides cheaper paths without hindering the blocking probability.

6. Conclusions and Future Work

In this paper, we presented a complete framework to handle routing in all-optical DWDM networks with limited wavelength conversion resources that can be applied to metro-core and long-haul optical networks. The routing framework presented in this paper includes an ILP formulation that solves the RWA problem in all-optical DWDM networks with limited wavelength conversion capabilities under Static Lightpath Establishment, an extension to the original OSPF protocol that floods necessary information about the availability of wavelengths and converters throughout the optical network domain, an adaptive flooding policy that avoids the exchange of unnecessary update messages while not hindering the blocking probability, and finally a heuristic based on fuzzy logic to
perform efficient route computation. Another important contribution of our work is that our framework and solutions are not specific to all-optical networks with limited wavelength conversion capabilities. Our models are generic and can be applied to wavelength constraint networks (no wavelength conversion capabilities), networks that have few wavelength conversion resources, as well as networks that have unlimited number of wavelength conversion resources (wavelength converters are always found when needed).

In this work, all wavelength converters are assumed to have full wavelength conversion capability. This means that each wavelength converter is capable of transforming any input wavelength to any desired output wavelength. Currently we are working on a simulation tool for routing in all-optical networks that compares the performance of our fuzzy-based routing heuristic with that of other adaptive routing (for example, least congested path, and shortest path) and wavelength assignment (for example, least-loaded, and most-used) heuristics presented in the literature. In the future, we plan to extend this work to handle networks with limited number of wavelength converters that might not support full wavelength conversion. This can help to achieve even lower costs for such networks.

| Rule 1: If (ConverterUtilization is HeavilyUsed) or (BandwidthUtilization is HeavilyUsed) then (UpdateInterval is FastUpdates) |
| Rule 2: If (ConverterUtilization is ModeratelyUsed) and (BandwidthUtilization is ModeratelyUsed) then (UpdateInterval is ModerateUpdates) |
| Rule 3: If (ConverterUtilization is LightlyUsed) and (BandwidthUtilization is LightlyUsed) then (UpdateInterval is SlowUpdates) |

Figure 5(a): Rule base for adaptive flooding policy.
Figure 5(b): Membership functions for adaptive flooding policy.
Figure 5(c): Example on computing the update interval using our fuzzy approach.

Figure 6(a): Comparison between the average number of updates exchanged using the instantaneous flooding policy and using our adaptive flooding approach.
Figure 6(b): Comparison between the blocking probability using the instantaneous flooding policy and using our adaptive flooding approach.

Figure 7: Fuzzy-based routing model for all-optical DWDM networks with limited wavelength conversion capabilities.
Rule 1: If (PathHops is LongPath) or (BandwidthCongestion is HighUtilization) or (ConverterCongestion is HighUtilization) or (PathConverters is High) then (OverallCost is VeryHigh)

Rule 2: If (PathHops is ShortPath) and (BandwidthCongestion is LowUtilization) and (ConverterCongestion is LowUtilization) and (PathConverters is Low) then (OverallCost is VeryLow)

Rule 3: If (PathHops is MediumPath) and (BandwidthCongestion is ModerateUtilization) and (ConverterCongestion is ModerateUtilization) and (PathConverters is Moderate) then (OverallCost is Moderate)

Rule 4: If (PathDiversity is LowDiversity) then (OverallCost is High)

Rule 5: If (PathDiversity is ModerateDiversity) then (OverallCost is Moderate)

Rule 6: If (PathDiversity is HighDiversity) then (OverallCost is Low)

Rule 7: If (PathCost is LowCost) then (OverallCost is Low)

Rule 8: If (PathCost is ModerateCost) then (OverallCost is Moderate)

Rule 9: If (PathCost is HighCost) then (OverallCost is High)

Figure 8(a): Rule base for fuzzy routing heuristic.
Figure 8(b): Membership functions for fuzzy routing heuristic.
Figure 8(c): Example on calculating the overall cost of a path.

Figure 9(a): Comparison between the blocking probabilities using shortest-path routing with first-fit wavelength assignment and using our fuzzy routing model with the most-continuous wavelength assignment approach.
Figure 9(a): Comparison between the average cost of the paths selected using the shortest-path routing with first-fit wavelength assignment and using our fuzzy routing model with the most-continuous wavelength assignment approach.
References


