Routing in all-optical DWDM Networks with Sparse Wavelength Conversion Capabilities

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Abstract— **This work focuses on the Routing and Wavelength Assignment (RWA) problem in all-optical DWDM networks with Sparse Wavelength Conversion (SWC) capabilities. By sparse wavelength conversion, we mean that nodes within the optical network domain might or might not support optical wavelength conversion. For these nodes that support optical wavelength conversion, the number of wavelength converters might be limited. As such, optical lightpaths might or might not be able to find the wavelength conversion resources that might be needed for it to be established. In this work, we present the RWA problem in all-optical WDWM networks with sparse wavelength conversion capabilities (RWA-SWC). We also provide Integer Linear Programming (ILP) formulation for Static Lightpath Establishment (SLE) in all-optical networks with sparse wavelength conversion capabilities. Finally, we propose a new opaque extension to the OSPF routing protocol to advertise wavelength usage and converter availability throughout the optical network domain.**

I. INTRODUCTION

The telecommunications industry is currently facing an unprecedented demand for more bandwidth that is substantially higher than that offered by electro-optic networks. Electro-optic networks use electrical form of the signals to switch network traffic from the source through some intermediate nodes towards the final destination. These networks also use electro-optical regenerators to strengthen the transmitted signals and their signal to noise ratios. These network are not fully utilizing the bandwidth [WENB] of the optical fiber (approximately 10 THZ) because they use a single carrier frequency (wavelength) that is modulated at a maximum speed of 40 Gbps. Dense Wavelength Division Multiplexing (DWDM) is considered a promising transmission technology that improves that utilization of optical fiber bandwidth.

Thus, future transmission networks should employ technologies that overcome electro-optical bottlenecks and offer better utilization of the optical fiber bandwidth. It is believed that all-optical DWDM networks will provide the answer to these challenges. These networks will eliminate the electro-optical bottlenecks by transmitting optical signals from source to destination without the need for electro-optical conversion. They will also offer better utilization of the available fiber bandwidth by modulating multiple carrier frequencies (wavelengths) allowing a single strand of fiber to carry multiple optical signals.

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. In this work we focus on the routing and wavelength assignment problem in all-optical DWDM transport networks with sparse wavelength conversion capabilities. The remainder of this paper is organized as follows. Section II provides an overview of the RWA problem in networks with the LWC constraint. Section III provides ILP formulation for the RWA-LWC problem. Section IV presents new opaque extension to the OSPF routing protocol to handle all-optical DWDM networks with LWC constraint. Section V presents our flooding policy Section VI concludes this study and discusses future extensions.

II. THE RWA-LWC PROBLEM

A lightpath is an end-to-end connection that might span multiple links in the optical DWDM network. In order to be able to establish lightpaths in all-optical DWDM networks, a signaling protocol is needed to request and set up the lightpath through the optical network. When a connection request arrives to the network through the User to Network signaling protocol (for example, OIF), the routing protocol (for example, OSPF) finds a route and assigns wavelength(s) to the incoming lightpath. Then the network-to-network signaling protocol is used to set up the lightpath through the optical network.

The problem of finding a route and assigning wavelength(s) to an incoming lightpath is known as the Routing and Wavelength Assignment (RWA) problem. Two types of switching systems can be supported within the optical network domain [ZANG]: Wavelength Selective Cross-Connects (WSXC) and Wavelength Interchanging Cross-Connects (WIXC). In wavelength selective cross-connects, wavelength conversion is not supported and a lightpath must occupy the same wavelength throughout its route from source to destination. This constraint is known as the wavelength continuity constraint. This means that a lightpath can be blocked even if there are available wavelengths on all links. Allowing the lightpath to change from one wavelength to another at an intermediate node can reduce the blocking

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probability. Switching systems that allow wavelength conversion are called Wavelength Interchanging Cross-Connects (WIXC).

Wavelength converters may lower the blocking probability in the optical network by resolving the conflicts between the lightpaths. A switching system that is capable of converting every single incoming wavelength to any other wavelength is called a full wavelength conversion capable system. An optical network that is composed of such switching systems is equivalent to a circuit-switched telephone network [ZANG]. In this case, the routing problem only needs to be solved and wavelength assignment is not an issue.

Unfortunately, wavelength converters are expensive and adapting full wavelength conversion solution within an optical network is an expensive strategy that does not always offer higher performance improvements in terms of lower blocking probabilities.

A more cost effective strategy can be adapted by distributing the wavelength conversion resources on all optical switches throughout the optical network domain. In this case, each switch has a limited number of wavelength converters that it can use to convert an incoming wavelength to another outgoing one.

In optical networks that posses LWC capabilities, the RWA problem is more challenging since each lighpath has to be assigned a route and a set of wavelengths depending on the availability of the wavelength conversion resources through the optical domain. It should be noted here that the RWA-LWC problem 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.

III. 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.
- $Q = \{q_i\}, i = 1,2,...,\Pi$: Vector of size **Π**, where element q_i represents the number of requested lightpaths between the i^{th} source-destination.
- $R = \{r_i\}, i = 1,2,...,\Pi$: Vector of size **Π**, where element r_i represents the number of all possible paths between the i^{th} source-destination pair.
- $V = \{v_i\}, i = 1,2,...,N$: Vector of size **N**, where element v_i represents the number of wavelength converters installed on the i^{th} node.
- $P^i = \{p^i_j\}, j = 1,2,...,r_i$: A list of **Π** 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.
- $U^i = (u^i_{j,k}), j = 1,2,...,r_i, k = 1,2,...,E$: A list of **Π** 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.
- $X^i = (x^i_{j,k}), j = 1,2,...,r_i, k = 1,2,...,N$: A list of **Π** 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.
- $Y^i = (y^i_j), j = 1,2,...,r_i$: A list of **Π** 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.
- $Z^i = (z^i_{j,k}), j = 1,2,...,r_i, k = 1,2,...,E*W$: A list of **Π** vectors that represent the usage of the wavelength resources (lambdas) by the different paths, vector Z^i is the i^{th} vector of the list. Element $z^i_{j,k}$ = 1 if the jth 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.
- $S^i = (s^i_j), j = 1,2,...,r_i$: A list of **Π** 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:

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

Subject to the following constraints:

$$S^i_j \leq 1 \qquad \forall \;\; 1 \leq i \leq \Pi \;\; 1 \leq j \leq r_i \qquad (1)$$

$$Q^i \leq \sum_{j=1}^{r_i} S^i_j \qquad \forall \;\; 1 \leq i \leq \Pi \qquad (2)$$

$$(S^i)^T U^i \leq W \qquad \forall \;\; 1 \leq i \leq \Pi \qquad (3)$$

$$(S^i)^T X^i \leq V_i \qquad \forall \;\; 1 \leq i \leq \Pi \qquad (4)$$

$$(S^i)^T Z^i \leq 1 \qquad \forall \;\; 1 \leq i \leq \Pi \qquad (5)$$

In this formulation, the symbol *T* indicates the transpose operation. Equation (1) indicates 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. Fig. 1 shows the topology of the network on which the lightpaths indicated in Table 1 need to be established. In this example, each wavelength converter was 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.

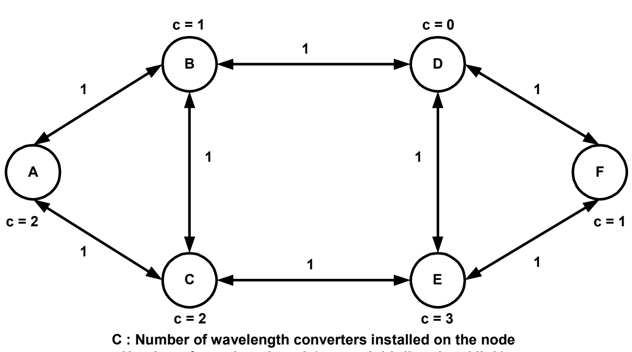

Figure 1: Sample network with LWC capabilities

Scenario	Source→Destination	Route	Wavelengths	Converters
A	A → F	AB → BD → DF	3 → 3 → 3	0 → 0
	A → F	AC → CE → EF	3 → 3 → 3	0 → 0
	E → A	EC → CA	1 → 1	0
	E → A	EC → CA	2 → 2	0
	E → B	ED → DB	2 → 2	0
	C → D	CB → BD	1 → 1	0
B	E → A	EC → CA	3 → 3	0
	E → B	ED → DB	1 → 1	0
	E → B	ED → DB	2 → 2	0
	E → B	ED → DB	3 → 3	0
	E → B	EC → CB	1 → 1	0
	E → B	EC → CB	3 → 3	0
	A → B	AB	1	0
	A → B	AB	2	0
	A → B	AB	3	0
	A → B	AC → CB	1 → 3	1

Table 1: Examples of route, wavelength, and converter assignment in LWC networks

IV. GENERIC OPTICAL ROUTING EXTENSION (GORE)

The Open Shortest Path First (OSPF) is an efficient and commonly used link-state protocol [MOY2] that can be employed to distribute QoS parameters through the optical network utilizing its flooding protocol and its opaque LSA option. In this section, we introduce a Generic Optical Routing Extension (GORE) to the OSPF Version 2 protocol described in RFC-2328. The purpose for this extension is to advertise the wavelength and converters availability throughout the optical network domain.

Earlier Internet drafts by Chaudhuri et al. [CHAU] and Basak et al. [BASA], take the stand that an optical adaptation of the OSPF protocol should not advertise any information pertaining to wavelength availability or wavelength converters' availability. They contend that the set of available wavelengths as well as the number of converters used to convert an ingress wavelength to a different wavelength at the egress of the switch change so frequently that advertising these changes would not yield a performance increase proportional to the communication cost of increased control traffic.

Our GORE extension breaks from their proposal and adopts a new strategy that consists of adapting the OSPF protocol to advertise the number of available wavelengths per fiber and the number of wavelength converters available within the switch. Our rationale for advertising wavelength availability information as well as the wavelength converters availability information is as follows.

In networks with sparse wavelength conversion capabilities, a significant number of switches do not posses a large number of wavelength converters; the absence of wavelength information from the description of network links causes the route computation algorithm to operate with insufficient information about the network state. As wavelength utilization of network links increases, the probability of selecting a source route that can be provisioned dramatically decreases because the limited number of wavelength conversion resources will render most of the source routes infeasible. It is unacceptable that the infeasibility of these routes would not be detected until signaling was attempted and failed, because this would cause lightpath setup to experience a large number of crankbacks. The cumulative effect of not advertising wavelength availability information as well as the switch wavelength conversion capability being that as the load on the network increases, the lightpath setup latency increases prohibitively. This problem gets worse when a large number of switches in the network have limited number of wavelength conversion resources.

It should be emphasized here that [KOMP01] is designed to handle a network comprised of Packet Switching Capable (PSC), Time Division Multiplexing Capable (TDMC), Lambda Switching Capable (LSC), and Fiber Switching Capable (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.

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 number of wavelength conversion resources. Even though that the routing extension presented in this paper is an overlay specific one that pertains to all-optical DWDM networks regardless of their wavelength conversion capabilities a similar approach can be adapted to design routing protocols for other overlays.

A. Overview OSPF-GORE Extension

OSPF opaque Link State Advertisement (LSA) option provides a generalized mechanism for OSPF to carry additional information especially for traffic engineering. Opaque LSAs [COLT] are of types 9, 10, and 11. Opaque LSAs consist of a standard LSA header followed by a 32-bit aligned application-specific information field. The traffic engineering LSA opaque data is divided into a number of tuples, each consisting of a Type (T), a Length (L), and a Value (V). The general definition of TLV is used, except that the length field size depends on the type field. The information carried by an opaque LSA is structured into one TLV and zero or more traffic engineering sub-TLVs as needed. Fig. 2 represents the detailed structure of an opaque LSA header while Fig. 3 represents the structure of the information carried by the opaque LSA in terms of TLV and sub-TLVs.

In the next two subsections, a detailed description of the message formats used by our OSPF-GORE extension to advertise the wavelength usage and the number of available wavelength converters per switch is illustrated.

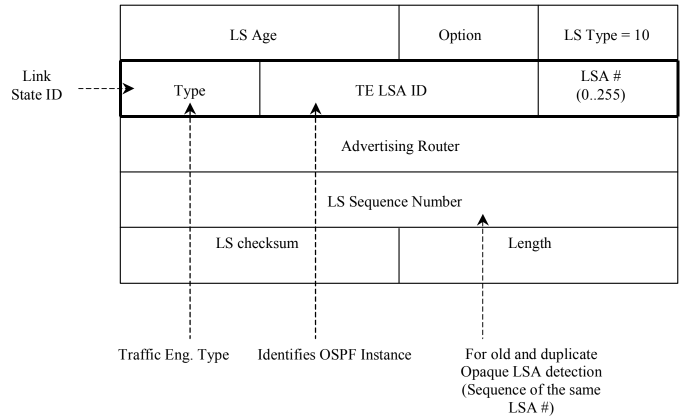

Figure 2: Opaque LSA header information

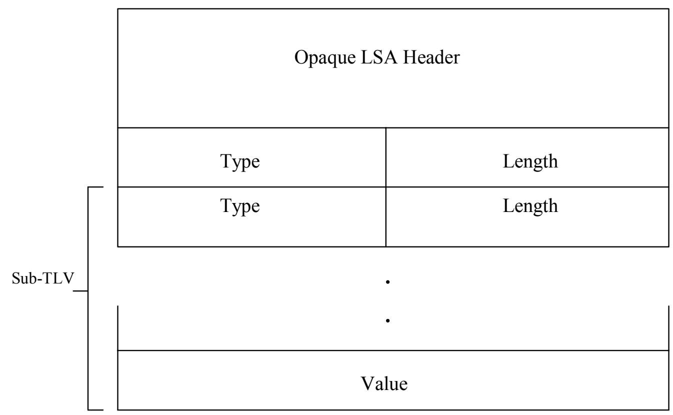

Figure 3: Opaque LSA structure

1) Wavelength-Availability Opaque LSA Message Format

The Wavelength-Availability Opaque LSA describes a DWDM link that can carry multiple wavelengths. This LSA describes the availability of the different wavelengths carried over the DWDM link, the local and remote interface IP addresses and their identifiers.

Fig. 3 shows the Wavelength-Availability Opaque LSA format. This LSA 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.

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- ***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.
- ***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 = 32777***: The type of the new introduced sub-TLV should be out of the range **32768-32772**, which is reserved for Cisco-specific extensions. Our OSPF-GORE extension range should not conflict with the required or optional sub-TLV types or with range reserved for Cisco-specific extensions. The range **32773-32777** will be used by OSPF-GORE for further extensions. We decide to assign a type value of *32777* to the new Wavelength-Availability opaque sub-TLV.
- ***Length of Mask***: Number of bits used to represent the bandwidth mask.
- ***Bandwidth Mask***: This field represents the available as well as used wavelengths over a specific link. This field is *120* bits long (see Fig. 4). Bit *i* (where $1 \leq i \leq 120$) represents the status of λ_i:

$\lambda_i = 1$ ➔ if wavelength λ_i is currently used
$\lambda_i = 0$ ➔ if wavelength λ_i is currently free

2) Wavelength Converter Availability Opaque LSA Message Format

The Wavelength Converter Availability Opaque LSA describes the number of wavelength converters available within the switch. We use the same concept used to define the Wavelength Availability opaque LSA except for the sub-TLV type field.

Fig. 5 depicts the Wavelength Converter Availability Opaque LSA format. This LSA contains the following fields:

- ***Type = 32776***: We use the same concept used in defining the Wavelength Availability opaque LSA. Again, the type of the newly introduced sub-TLV should be out of the range **32768-32772**. We decide to assign a type value of *32776* to the Wavelength Converter Availability opaque sub-TLV.

- ***Number of converters***: The total number of converters that are not used within the switch.

V. OSPF-GORE LSA FLOODING POLICY

Some of the Traffic Engineering (TE) and Quality of Service (QoS) parameters change very frequently, raising the issue of when to advertise the changes of the network characteristics throughout the whole network. The original OSPF standard mandates a variety of tunable parameters controlling the flooding of LSAs, including the *MinLSInterval* that specifies the time between any two consecutive LSA originations, and the *MinLSArrival* that limits the frequency of accepting newer instances of LSAs.

In [APOS], Apostolopoulos et al. present other policies dealing with the issue of when a router should flood a new LSA to advertise changes in its link metric. Some of the proposed policies include:

- Threshold based policies, which trigger updates when the difference between the previously flooded and the current value of available link bandwidth is larger than a configurable threshold.
- Class based policies, which partition the capacity of a link into a number of classes and re-advertise when a class boundary is crossed.
- Timer based policies, which generate updates at fixed intervals to enforce a minimum spacing between two consecutive updates.

Our OSPF-GORE extension adopts the following update policy to advertise the wavelength usage and converter availability metrics:

- The traffic coming to the switch over a specific wavelength uses the same wavelength at the output port of the switch: In this case, no wavelength conversion is needed and only a Wavelength Availability LSA has to be originated and flooded to all neighboring switches.

- The traffic coming to the switch over a specific wavelength needs to be switched to a different wavelength at the output port of the switch: In this case, a wavelength converter is needed and two opaque LSAs have to be originated and flooded to all neighboring switches. The first opaque LSA is the Wavelength Availability, which refers to the change in the wavelength availability. The second opaque LSA is the Wavelength Converter Availability, which refers to the change in the available number of converters within the switch.

VI. Conclusions and Future Work

In this work, we introduced a new extension to the OSPF routing protocol for all-optical DWDM networks with sparse wavelength conversion capabilities. We also presented an ILP formulation for the RWA-LWC problem faced in these networks. This ILP formulation can be used in small networks with static traffic load. In the future, a heuristic approach can be introduced to deal with large networks or networks with dynamic traffic loads. The objective of any proposed heuristic should be to minimize the blocking probability while offering paths with reasonable QoS. A fuzzy-inference rule base can be used to assign a fuzzy cost to each path based on the crisp metrics of the network links and the QoS requirements of the lightpaths that need to be established.

LS Age	Option	LS Type=10
TE Type	TE LSA ID	LSA#
Advertising Router		
LS Sequence Number		
LS checksum	Length=108	
Type=2	Length=84	
Type=2	Length=4	
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	
Link Protocetion Type	Not Used	
Type=32774	Length=8	
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: Wavelength availability opaque LSA

LS Age	Option	LS Type=10
TE Type	TE LSA ID	LSA#
Advertising Router		
LS Sequence Number		
LS Checksum	Length=32	
Type=2	Length=8	
Type=32776	Length=4	
Number of Converters	Number of Used converters	

Figure 5: Converter availability opaque LSA

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