Cross Layer Routing in Optical IP/WDM Multi-Domain Networks

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Abstract — Dense Wavelength Division Multiplexing (DWDM) has emerged as the premiere transport technology and has gained much traction in long-haul and metro/regional networks, while most of the Internet services have been converged on the Internet Protocol (IP) layer. This has motivated the expectation that IP over WDM multilayer infrastructure to be the preferred infrastructure for broadband communications in the near future. However, routing and connection setup in multi-domain networks that considers both multilayer routing policies Physical Topology First (PTF) and Virtual Topology First (VTF) to handle circuit switched connection setup on both IP and optical WDM layers in multi-domain networks is not yet investigated sufficiently. In this paper, we propose a routing scheme that can route a connection either on the optical or on the IP layer, which gives the opportunity to use the multilayer routing policies PTF and VTF in multi-domain network.

Keywords-component; DWDM; IP/WDM; multi-domain multilayer; ASON; GMPLS

I. INTRODUCTION

The continually increase of bandwidth demand because of modern telecommunication networks has raised new challenges to the future Internet; therefore a need projected for a new Internet network infrastructure that can support the predicted huge demand for data traffic. DWDM has emerged as the premiere transport technology and has gained much traction in long-haul and metro/regional networks [1]. The invention of circuit-switching capable devices such as Optical Cross-Connect (OXC) or Optical Add-Drop Multiplexer (OADM) devices was an expected result. However an adequate architecture still needed, therefore has IETF has proposed the Generalized Multi-Protocol Label Switching (GMPLS) framework [1]. This adapted packet-based Multi-Protocol Label Switching (MPLS) protocols to support circuit-switched connections. Additionally GMPLS provides significant features for routing, signaling, and link discovery [2]. This integrated infrastructure provided GMPLS with the capability to combine packet-based and circuit-switched technologies together [3, 4].

MPLS protocols have been adjusted to allow OXC to setup Optical Label Switched Paths (OLSPs) automatically, whereas labels are represented by wavelengths λ [3,4,5].

The International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) has motivated the idea of management, routing and signaling in order to provide an automated optical connection setup, which avoids slow and error prone manual involvement. This has resulted the innovation of Automatically Switched Transport Network (ASTN), formerly ASON (G.8080). However ASON is only an architecture that defines the components in an optical control plane and the interactions between these components, but it does not define a protocol or collection of protocols. This has encouraged it association with GMPLS. This and the success of IP-based MPLS called IP/MPLS have motivated the IP/MPLS over ASON/GMPLS network architecture. This has produced the known Multilayer Traffic Engineering (MTE) paradigm in an incorporated routing manner [6, 7, 8, 9]. These techniques give the possibility to accommodate requested connections on both layers the IP/MPLS layer and on the optical WDM layer, in former case traffic accommodation is done by aggregating traffic on the available capacity in the IP/MPLS domain, which is called grooming technique. In the latter connection setup is done via the creation of a new optical connection in the optical domain. This cross-layer interaction optimizes usage of resources, which increases the Return on Investment (ROI), which makes IP/MPLS over ASON/GMPLS networks projected to be the favorite architecture for the future Internet [8].

It is known that Internet consists of more than 29.000 networks, every one of them known as domain or Autonomous Systems (AS), which are interacting autonomously in a decentralized manner. In this structure, selecting a route to forward traffic in an end to end scenario is known as multi-domain or inter-domain routing.

Routing in multi-domain networks have been largely analyzed packet switched networks, which is not the case in circuit switched optical multi-domain networks. Security and scalability are major challenges. It is obvious that network operators would not maintain the full state information of their network across all domains; consequently it is crucial to find a way to aggregate and propagate information across domains while keeping the domain internal resources like physical links, link diversity, and available resources hidden from exterior domain operators. This provides also the privilege to avoid traffic overload coming from carrying routing information.
Topology abstraction has been proposed as a solution for these routing challenges in multi-domain but the fact that all routing information must be available for all participant nodes within a single domain has exposed the need for different routing information levels, which is known as hierarchical routing.

Previously Topology abstraction and hierarchical routing techniques have been investigated and tested in packet-switched and cell-switched asynchronous transfer mode (ATM) networks [10, 11].

This study proposes a routing scheme, which supports routing in both the IP and optical layers in multi-domain end to end scenario, which provides the options to accommodate the traffic in an inter-domain either on the available capacity on the IP layer or if needed to setup the traffic directly on the optical layer, which gives the opportunity to apply the routing policies PTF and VTF in the multi-domain multilayer networks, and opens the gate to apply Quality of Service (QoS) based on these routing policies.

II. BACKGROUND AND RELATED WORK

A. Technical background

MPLS and GMPLS have elected Open Shortest Path First (OSPF) as routing protocol. OSPF has been extended with Traffic Engineering (TE) feature, which has been defined by RFC 3630 [12]. In [13] the authors have introduced OSPF-TE, which proposes an extended link state database to advertise additional link attributes that support QoS routing in GMPLS networks.

Also IETF has included the new OSPF-TE opaque Link State Advertisement (LSA) in GMPLS for DWDM and SONET/SDH links, enabling TE databases (TEDBs) to store wavelengths/usages, timeslots/usages, shared risk link groups (SRLGs), etc.

The signaling protocol Resource Reservation Protocol has been also extended to support TE features, (RSVP-TE). This has made the applicability of GMPLS in multi-domain settings more attractive.

OSPF-TE supports multiple link granularities; therefore it is adequate for inter-domain routing, as a unified inter-domain link-state solution. For signaling in multi-domain, provides RSVP-TE many options, via its loose Route (LR) feature, it supports the specification of partial skeleton routes, and succeeding explicit route (ER) expansion can be used to determine a full Label Switched Paths (LSPs) [2]. Additionally RSVP-TE defines mechanisms to setup LSP across domain boundaries — contiguous, stitched, and nested [14, 15]. Consequently the TE feature that provides load balancing for IP/MPLS networks has been integrated with the ASON/GMPLS layer. This has resulted in the MTE paradigm and cross layer routing.

B. Related Work

Several studies have addressed the routing issue in optical multi-domain networks. The study in [18] addressed the problem of lightpath provisioning in SONET-DWDM multi-domain networks. Therefore the authors have defined a multi-segment graph model, which has been used to assess three path selection schemes; whereas the first one proposes a centralized (full-knowledge) routing scheme and selects the E2E using global shortest path algorithm. The problem of this scheme is that is cannot be used in networks, if detailed routing information cannot be entirely exchanged. The second is (local knowledge) domain-by-domain based routing; whereas each segment decides the route and allocates wavelengths only based on local information. Gateways choose based on the segments interconnection information the next segment to the destination. The third schemes is based on partial inter-domain knowledge and uses hierarchical source routing, which make it as a compromise between the first and second routing scheme. However the third scheme propagates domain state only for particular granularities; furthermore state aggregation scheme is not explained, whereas the results illustrate that the blocking probability is much lower if the level of inter-domain state propagation with increased levels of inter-domain state propagation.

The study in [19] proposes a comprehensive GMPLS based DWDM network using IP/WDM routers; a hierarchical routing setup is adapted along with full-mesh topology abstraction scheme. In [20] the authors present a detailed IP/MPLS based ASON/GMPLS multi-domain framework to address the problems of routing and traffic grooming in optical multi-domain multi-layer networks. The authors in [21] have proposed a methodology to address the problems of routing, connection setup, and traffic grooming in optical multi-domain networks, which adapts a two-level hierarchical routing scheme and full-mesh topology abstraction algorithm to improve routing scalability and lower inter-domain blocking probabilities; additionally the proposed methodology adapts a scheme for traffic grooming in DWDM multi-domain networks to improve the resources usage. However the studies of [19, 20, 21] proposed an inter-domain routing scheme considers only the IP virtual layer, while routing on physical WDM layer was not incorporated, which make the Optical-Electronic-Optical (OEO) conversion at the border nodes a must.

Also in the authors of [22] proposed an integrated direct Ethernet-DWDM, which uses an integrated multi-domain signaling to lightpaths provisioning and grooming on sub-rate circuits. However, the authors assumed the underlying DWDM networks to be static; therefore routing is performed only at the Ethernet layer.

The analysis of related work shows that multilayer routing in optical multi-domain networks has gained a lot of attention recently, but a detailed study to test the cross layer routing to accommodate the traffic on both layers the IP and physical WDM layer is still lacking. In this study we address the challenges of cross layer routing and connection setup on the IP and WDM layers in IP/WDM multi-domain optical networks.

III. INTEGRATED IP/WDM NODE MODEL AND NETWORKS TEST FRAMEWORK

In the simulations to this work, we consider a simplified model of integrated IP/MPLS over optical networks where every node has the architecture presented in [8]. This node model allows the operators to manage the IP and optical domains as a single layer, which enables cross-layer designs
and optimizes the resource usage, which decreases the OPEX/CAPEX [6].

Because of the requirement for security and scalability in multi-domain networks, we developed a test framework for distributed cross layer routing in IP/WDM multi-domain networks, which adapts hierarchical routing and topology abstraction. Therefore our proposed routing scheme uses a two-level hierarchical routing approach, where border nodes are designated in each domain as a routing area Leader (RAL) [2]. Therefore in this hierarchy the lower level that is responsible for intra-domain routing and the higher level routing operates between border nodes (RAL) and exchanges inter-domain state. We used this higher level to provide a global summary of link resources of each domain, including physical and virtual links. Therefore in our test framework we invented a Full-Mesh (FM) topology algorithm, which is evolved from earlier proposals for data/cell switching networks [6] and performs intra-domain state summarization. Our proposed FM algorithm summarizes the available physical resources by creating virtual links between each pair of border nodes within the same domain, where the state of each virtual link indicates the number of available wavelengths between each pair of border node and can be used for an inter-domain connection. Additionally we made the information in the higher level about the available capacity of any Light path (OLSP) connects any pair of border nodes available in order to setup an inter-domain LSP. Accordingly, the domain is transformed into a graph containing the border nodes interconnected via a fully meshed set of virtual links indicating the available wavelengths and the available capacity on each lightpath connects between any pair of border nodes within the same domain, which makes cross layer routing on WDM optical layer and IP layer feasible. The FM topology algorithm for creating the virtual links indicating the available wavelength is triggered by a timer and loops between all border nodes (see subsection B in section 3).

A. Node model

As mentioned above in our simulation framework we are using an IP/WDM node, which consists of a hybrid architecture includes an IP/MPLS packet switching fabric and a fiber/wavelength switching fabric, which enables cross-layer routing and makes the node capable to be perform each or both of the following functionalities:

1. The IP/MPLS can work as a start, switching or termination point of a LSP. The traffic, which comes in optical form from an input OLSP is converted into electronic format and forwarded to the IP/MPLS router to perform the label swapping operation. After that the packets is reconverted into optical format and forwarded into the output OLSP.

2. The node can function also as an OLSP switching fabric. If the traffic is carried over an optical lightpath with a certain wavelength enters the node through an input fiber. Whereas the label swapping is performed on optical layer and bypasses the IP/MPLS router. With other words, according to the decision taken by the control protocols, the signal is transformed to another wavelength and placed onto an output fiber.

B. Topology Abstraction

In our test framework we introduce a FM topology abstraction scheme, which summarizes the physical resources available in a single domain state (see Figure 2).

Our proposed algorithm for abstracting the physical resources and computing the full-mesh graph transformation is shown in figure 3.

It is running in each border node (RAL) in each domain and uses the shortest open path to compute the virtual links connecting each pair of border nodes (RAL) within a domain, while these virtual links indicate the available physical resources (wavelength) in the physical domain. The information of these computed virtual FM graph are made available to other border nodes in the entire network. For the accuracy of the routing information a timer triggers FM algorithm periodically to update the abstracted FM topology.
IV. INTER-DOMAIN ROUTING IP/WDM MULTI-DOMAIN NETWORKS

As explained above for reasons of security and scalability, it is obvious that aggregation of routing information is essential in multi-domain networks. This is feasible using hierarchical routing and topology abstraction. However the integrated IP/WDM routing facilitates the routing decision phase by allowing a node to have a complete knowledge of the IP and WDM domains when accommodating traffic. Therefore introducing hierarchical routing is indispensable.

A. Hierarchical routing

In this work we propose a hierarchical multi-domain routing scheme, which is using the FM topology aggregation explained above. In view of that we introduce a two level hierarchical routing scheme, whereas the border nodes in each domain are designated as RAL [2].

The designated RALs have in addition to the full routing information knowledge about its own domain network topology, the knowledge about all the abstracted routing information on the higher level topology. This includes the inter-domain links, the virtual links connecting border nodes in each domain indicating the available wavelengths and the available capacity on each lightpath connects between border nodes (RAL). This information can be then used to setup end-to-end inter-domain LSP using new inter-domain OLSP or to groom a new LSP in the IP/MPLS domain.

B. Inter-domain connection setup

In our proposed scheme for inter-domain routing and LSP connection setup we use the LR supported by the distributed Resource ReserVation Protocol- Traffic Engineering (RSVP-TE) [23] to perform the inter-domain path computation. The setup sequence for an inter-domain connection is originating at an interior source node and destination node. The scheme uses OSPF-TE to setup a new connection (Figure 4).

Figure 4 Illustrates the computation of an Inter-domain LR for a new LSP connection, which is done using OSPF-TE algorithm, if source node has received a request for connection, it computes the route to the closest border node (RAL) within the same domain, this designated RAL selects a RAL in the destination domain based on the computation of the shortest inter-domain route to the destination domain and returns an end-to-end LR sequence of border nodes specifying the route to the destination domain, e.g., ingress border node at the source domain, all ingress/egress border nodes at intermediate domains, and final ingress border node at the destination domain, afterwards it updates the route originates at the source node. This computation is maintained over the virtual inter-domain topology graph (see Figure 4), (Note: if the source node is also a border node, LR computation can be done locally). Afterword the selected destination RAL computes the route to the destination node, and then updates the route. For simplicity we proposed in our framework that all nodes are equipped with wavelength conversion.

When the destination router receives the path message it will make the admission and reservation on the IP or WDM layer based on the request parameters, and then it forward the Reservation message upstream (see figure 4).

Figure 4 Inter-domain LSP connection setup
V. PERFORMANCE EVALUATION

To test our proposed cross layer routing in IP over WDM networks we have developed an IP/WDM multilayer multi-domain network using the simulation tool OMNET++ [24].

The test network consists of three domains, which are connected with four unidirectional inter-domain links to stress inter-domain performance and ensure good inter-domain connectivity (Figure 5), which makes the averaging inter-domain links per domain is 2.67.

The requests for connections are generated by a connection generator, while the source and destination of each request is selected randomly via a uniform distribution. Additionally the requests for connection are generated based on 70/30 intra/inter-domain ratio. This is chosen to reflect practical networks which are likely to field more intra-domain requests for connection.

VI. SIMULATION RESULTS

The metric of interest is the connection blocking ratio and the average length of LSPs by different traffic load and different wavelength number, therefore we consider the traffic injected into the network as a set of connection requests. $C_{req}$ is the capacity requested by the connection, which is randomly chosen according to a uniform distribution between 10% and 30% of the OLSP channel capacity. To calculate the connection blocking ratio, we run simulations with $10^6$ requests.

Figure 6 highlights the effect of the availability of physical resources (wavelengths) on the locking probability; therefore we present the blocking probability by $32\lambda$, $16\lambda$, $12\lambda$ and $8\lambda$. As it is to be expected that the available physical resources affect the blocking ratio, which is noticed clearly from the higher blocking ratio when a smaller number of available wavelengths.

Figure 7 illustrates a comparison of the LSPs length as a count of lightpaths (OLSPs). This is done under different traffic loads and for different number of available wavelength. The results illustrate the effect of availability of physical resources on length of LSP and shows that our proposed cross layer routing scheme will make it possible to accommodate more traffic on physical layer on an inter-domain lightpath if the physical resources are available, where a LSP can be accommodated on less number of OLSP, which makes the LSP shorter.

VII. CONCLUSION AND FUTURE WORK

We presented in this work a cross layer routing scheme for optical multilayer multi-domain networks. Therefore we developed and used a comprehensive framework that supports lightpath provisioning and traffic accommodation on an IP/WDM networks. Our routing scheme is based on two level hierarchical routing using an FM topology abstraction algorithm to keep the security restrictions and to improve routing scalability.
Compared to related work, our routing scheme provide the possibility to route the inter-domain traffic on both layers the IP and physical WDM, which improves the resources usage and can avoid the inescapable OEO conversion at the border nodes, which is required if the inter-domain routing is performed only on the IP layer.

As our proposed routing scheme for GMPLS based DWDM multi-domain supports the traffic accommodation on the WDM physical layer and IP layer, it makes the application of PTF and VTF in multi-domain optical networks possible, which counts as the first milestone toward the application of service differentiation in optical multi-domain networks. This will be the focus of our next research works.

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