**PERFORMANCE ANALYSIS OF HIERARCHICAL INTER-DOMAIN ROUTING IN OPTICAL DWDM NETWORKS**

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**ABSTRACT**

Dense wavelength division multiplexing (DWDM) has become the dominant transport layer technology for next-generation backbone networks due to its unprecedented capacity scalability. As a result, there is a pressing need to investigate light path provisioning in multi domain DWDM networks. Although inter-domain provisioning has been well-studied for packet/cell-switching networks, the wavelength dimension (along with wavelength conversion) presents many added challenges. To address these concerns, a detailed GMPLS-based hierarchical routing framework for provisioning transparent/translucent/opaque multi-domain DWDM networks is presented. The scheme adapts topology abstraction to hide internal domain state so as to resolve routing scalability and security issues. Specifically, a novel full-mesh topology abstraction scheme is developed for full wavelength conversion domains, i.e., to disseminate additional wavelength converter state. Related inter-domain Light path RWA and signaling schemes are also tabled. Performance analysis results are then presented to demonstrate the effectiveness of the proposed mechanisms along with directions for future research work.

**INTRODUCTION**

Dense wavelength division multiplexing (DWDM) has emerged as the premier transport technology and has gained much traction in long-haul and metro/regional networks. DWDM exploits the huge unused spectrum in single mode fiber (SMF) to transmit multiple channels at unprecedented Tera bits/s speeds. As this technology has matured, a wide range of circuit-switching capabilities have evolved, e.g., optical cross-connect (OXC) and optical add/drop multiplexer (OADM) devices. Additionally, there has been much progress in architectures and frameworks for optical networks. Namely, the IETF generalized multi-protocol label switching (GMPLS) framework has adapted packet-based multi-protocol label switching (MPLS) protocols for provisioning “non-packet” circuit-switched connections i.e., via label abstractions for wave lengths, timeslots, etc. GMPLS includes key additions for routing, signaling, and link discovery. Concurrently, the ITU-T has specified a broad-based automatic switched optical network (ASON) framework as well. On the algorithmic provisioning side a multitude of DWDM routing and wavelength assignment (RWA) and survivability schemes have been evolved. Multi-layer grooming schemes between DWDM and SONET or IP networks have also been addressed in detail; see survey in. However, most of these efforts have focused on single domain networks. Clearly, as DWDM technology proliferates there is a pressing need to develop more advanced light path provisioning algorithms for distributed multi-domain settings, i.e., as delineated by administrative or technological boundaries. In particular, emergent applications in the fields of grid-computing and e-science are driving the need for distributed, dynamic circuit switched interconnection at very large speeds. As the number of DWDM domains increases, it becomes difficult for a single entity to maintain state across all domains, e.g., physical links, available resources, link diversity, etc. Indeed, it is evident that some form of information aggregation and distribution is necessary between domains. Furthermore, there is a commensurate need for inter-domain light path RWA algorithms that use this aggregated state. This can be achieved by leveraging hierarchical routing and topology abstraction techniques which have been well-studied for packet-switching IP and/or cell-switching asynchronous transfer mode (ATM) networks. For example, the ATM Forum’s private network to network interface (PNNI) protocol clusters nodes into peer groups and uses topology abstraction to hide internal state from outside users. However,
many of these principles have only been proposed within the context of multi domain wavelength-sensitive DWDM networks, and detailed studies remain to be done. This thesis addresses the important area of distributed inter-domain provisioning in DWDM networks and builds upon the high-level schemes outlined in. Namely, a two layer hierarchical routing model is developed using the GMPLS framework for all-optical and optoelectronic multi-domain networks. This solution defines two topology abstraction algorithms and also tables associated inter-domain light path RWA and signaling schemes. In light of the above, there is growing need to develop scheme to provision guaranteed bandwidth connections across multiple IP/MPLS and/or optical DWDM domains. Ideally, these schemes should yield effective provisioning and high scalability along these lines GMPLS offer a very promising approach for developing new solutions for the multi-domain TE. Namely, it is envisioned that these resultant schemes will potentially yield very good performance gains (in terms of blocking) at the same time as reducing overheads. However even though some GMPLS schemes have been studied, most of these strategies pursue more basic “exhaustive” search methodologies and hence entail significant signaling overheads. Moreover, none of these solutions have been gauged against alternate hierarchical routing schemes. Along these lines the focus of this thesis is to study the design of advanced inter-domain light path provisioning strategies.

**PROPOSED WORK**

Distributed inter-domain DWDM provisioning is a challenging problem as the wavelength dimension poses added complications. Herein, a comprehensive framework is developed for distributed multi-domain light path RWA in both all-optical and hybrid opto-electronic networks. In the latter it is assumed that only the border nodes are conversion-capable and the interior nodes remain all-optical. This is a very realistic modeling of emergent optical networks, e.g., all-optical “islands” delineated with optoelectronic border nodes. The proposed scheme addresses several key steps in inter-domain provisioning. Foremost, a multi-domain topology abstraction model is defined to condense domain-level DWDM state. Subsequently, inter domain routing and triggering policies are derived to disseminate both physical/abstracted inter-domain state. Note that this favors link-state routing implementations which are more suitable for the added dimensionalities of DWDM networks. Finally, inter-domain light path RWA and signaling schemes are developed to setup light paths.

**OPTICAL NETWORKS**

Optical networks are high-capacity telecommunications networks based on optical technologies and component that provide routing, grooming, and restoration at the wavelength level as well as wavelength-based services. The origin of optical networks is linked to Wavelength Division Multiplexing (WDM) which arose to provide additional capacity on existing fibers. The optical layer, whose standards are being developed, will ideally be transparent to the SONET layer, providing restoration, performance monitoring, and provisioning of individual wavelengths instead of electrical SONET signals. So in essence a lot of network elements will be eliminated and there will be a reduction of electrical equipment.

It is possible to classify networks into three generations depending on the physical-level technology employed. First generation networks use copper-based or microwave technologies ex Ethernet, satellites etc. In second generation networks, these copper links or microwave links with optical fibers. However, these networks still perform the switching of data in the electronic domain though the transmission of data is done in the optical domain. Finally we have the third generation networks that employ Wavelength Division Multiplexing technology. They do both the transmission and the switching of data in the optical domain. This has resulted in the onset of tremendous amount of bandwidth availability. Further the use of non-overlapping channels allows each channel to operate at peak speeds. A network consists of a collection of nodes interconnected by links (In any topology). The links require “transmission equipment,” while the nodes require “switching equipment.” Technology developments to date have taught us that optics is fantastic for transmission, e.g., an optical amplifier can simultaneously amplify all of the signals on multiple wavelength channels (perhaps as high as 160) on a single fiber link, independent of how many of these wavelengths are currently carrying live traffic.
The model shown in Fig. 3.1 shows the physical topology of an IP over optical network. It consists of two layers: the optical core layer, the service provider layer. The optical layer is interconnected with the electronic layer which is also known as IP layer. IP and optical network are treated as a single integrated network for control purposes in a transmission process.

Services are not specifically defined at IP-optical interface, but folded into end-to-end MPLS services. Routers may control end-to-end path using traffic engineering (TE)-extended routing protocols deployed in IP and optical networks.

An optical network is not necessarily all-optical, the transmission is certainly optical, but the switching could be optical, or electrical, or hybrid. Also, an optical is not necessarily packet-switched. It could switch circuits, or sub-wavelength-granularity bandwidth pipes, or "bursts,” where a burst is a collection of packets. Based on the various optical technologies, the most prevalent deployment of optical networks today consists of optical-electrical-optical (OEO) switches (also called opaque switches), with each input operating at OC-192 (approx. 10 Gbps) rate. However, inside the OEO switch, each input channel can be de-multiplexed into STS-1 timeslots” and the switch can perform switching at STS-1 granularity. Thus, a network operator can support a variety of connection requests ranging in bandwidth from STS-1 to OC-192.

**Wavelength Division Multiplexing (WDM)**

Wavelength-division multiplexing (WDM) is a technique that can exploit the huge opto-electronic bandwidth mismatch by requiring that each end user's equipment operate only at electronic rate, but multiple WDM channels from different end-users may be multiplexed on the same fiber. Thus, by allowing multiple WDM channels to co-exist on a single fiber, one can tap into the huge fiber bandwidth, with the corresponding challenges being the design and development of appropriate network architectures, protocols, and algorithms. End-users in a fiber-based WDM backbone network may communicate with one another via optical (WDM) channels, which are referred to as lightpaths. A light-path may span multiple fiber links, e.g., to provide a "circuit-switched" interconnection between two nodes which may have a heavy traffic flow between them and which may be located “far” from each other in the physical fiber network topology. Each intermediate node in the light-path essentially provides an optical bypass facility to support the light-path.

**Transmitter:** The optical transmitter converts the electrical signal into optical form and launches the resulting optical signal into the optical fiber see fig. 2. It consists of an optical source, a modulator, and a channel coupler.
Semiconductor lasers or light-emitting diodes are used as optical sources because of their compatibility with the optical-fiber communication channel. The optical signal is generated by modulating the optical carrier wave.

**Fig 3: A wavelength division multiplexing scheme usually comprised of following System**

**Communication Channel:** The role of a communication channel is to transport the optical signal from transmitter to receiver without distorting it. Most light-wave systems use optical fibers as the communication channel because silica fibers can transmit light with losses as small as 0.2 dB/km. Even then, optical power reduces to only 1 percent after 100 km. For this reason, fiber losses remain an important design issue and determine the repeater or amplifier spacing of a long-haul light-wave system. Another important design issue is fiber dispersion, which leads to broadening of individual optical pulses with propagation. If optical pulses spread significantly outside of their allocated bit slot, the transmitted signal is severely degraded. Eventually, it becomes impossible to recover the original signal with high accuracy. The problem is most severe in the case of multimode fibers, since pulses spread rapidly because of different speeds associated with different fiber modes. It is for this reason that most optical communication systems use single-mode fibers. Material dispersion (related to the frequency dependence of the refractive index) still leads to pulse broadening, but it is small enough to be acceptable for most applications and can be reduced further by controlling the spectral width of the optical source.

**Receiver:** An optical receiver converts the optical signal received at the output end of the optical fiber back into the original electrical signal. It consists of a coupler, a photo-detector, and a demodulator. The coupler focuses the received optical signal onto the photo-detector. Semiconductor photodiodes are used as photo-detectors.

**Wavelength Cross connector:** Wavelength cross connector is a switching device whose function is to switch or connect any wavelength from the input port to any one of the output port in the fiber. The functioning is completely in optical domain. An OXC with N input and N output ports capable of handling wavelengths per port can be thought as W independent N×N optical switches.

**Dense Wavelength Division Multiplexing (DWDM)**

Light has an information-carrying capacity 10,000 times greater than the highest radio frequencies. It is seen that due to transmission of signal in an optical medium, signal strength will be reduced, known as attenuation loss. Further developments in fiber optics are closely tied to the use of the specific regions on the optical spectrum where optical attenuation is low. These regions, called windows, lie between areas of high absorption. The earliest systems were developed to operate around 850 nm, the first window in silica-based optical fiber. A second window (S band), at 1310 nm, soon proved to be superior because of its lower attenuation, followed by a third window (C band) at 1550 nm with an even lower optical loss. Today, a fourth window (L band) near 1625 nm is under development and early deployment. Dense Wavelength Division Multiplexing (DWDM) is an important technology in nowadays fiber optic network. DWDM and CWDM both use WDM technology to arrange several fiber optic lights to transmit simultaneously via the same single fiber optic cable, but DWDM carry more fiber channel compared with CWDM (Coarse Wavelength Division Multiplexing). DWDM is usually used on fiber optic backbones and long distance data transmission and DWDM system has higher demand of fiber amplifiers. Due to DWDM technology, a single optical fiber capacity nowadays could reach...
Routing and Wavelength Assignment (RWA)

In WDM, different channels are established simultaneously in a single fiber and large numbers of wavelengths are used for implementing separate channels. With WDM a single fiber can accommodate 120 channels now days and more in future. Efficient routing and wavelength assignment is an important issue in the WDM system. RWA is a unique feature of WDM network in which the process of data path selection i.e., the selection of path for a particular connection request with specified source destination edge nodes and then reserving one particular wavelength for the selected path occurs. For establishing a connection in the WDM network, we should consider both selection of data path i.e. routing and wavelength assignment for the selected route.

Routing Algorithms

**Fixed routing** In this algorithm, It is a simple algorithm, but the availability of effective light paths in the network is minimum hence blocking will be more. Hence it is not a resource efficient utilized routing technique.

**Fixed alternate routing** Here several alternate paths are calculated offline for a source destination pair. This method of routing provides alternate paths for a connection request hence link failure problem can be solved. The blocking probability also reduces if we go for fixed alternate routing technique.

**Adaptive routing** In this method, paths are calculated online depending on network state and availability of resources in the network. This is the most efficient routing algorithm for WDM network.

**Inter-domain routing**

Distributed inter-domain DWDM provisioning is a challenging problem as the wavelength/converter dimension poses many restrictions. Herein a comprehensive framework is developed for distributed multi-domain light path RWA in both all-optical and hybrid opto-electronic networks. In the latter it is assumed that only the border nodes are conversion-capable and the interior nodes remain all-optical.

**Topology abstraction**

Topology abstraction is used to summarize domain-level state. In particular the proposed hierarchical scheme designates a specific border OXC node in each domain as a routing area leader (RAL). This entity computes a DWDM topology abstraction for its domain by transforming the physical topology into a virtual topology. Specifically, two abstraction schemes are presented, i.e., simple node and full-mesh, as evolved from earlier proposals for data-cell-switching networks. Note that more advanced star abstractions are left for future study. The virtual state information (as generated via the abstractions) is then flooded to border OXC nodes across all domains using inter-domain routing protocols. These helps maintain a synchronized global virtual view of the whole network and allow abstracted information to be used to compute end-to-end inter-domain light paths. To detail the topology abstraction scheme, it is first necessary to develop the required notation. Here all set and vector entities are denoted in bold and it is assumed (without loss of generality) that fiber connectivity is bi-directional, i.e., there are two opposite-direction fiber links between a pair of connected OXC nodes. Consider a DWDM network comprising D domains, with the ith domain having ni nodes and bi border/gateway OXC nodes, 1 ≤ i ≤ D. This network is modeled as a collection of domain sub-graphs, G_i^t(V_i^t, L_i^t), 1 ≤ i ≤ D, where V_i^t = {v_i^1, v_i^2, ..., v_i^n_i} is the set of physical domain OXC nodes and L_i^t = {E_i,k} is the set of physical intra-domain links in domain i(1 ≤ i ≤ D,1 ≤ j0, k ≤ n_i), i.e., {E_i,k} is the link between OXC nodes v_i^j and v_i^k. All links have W wavelengths. Furthermore, B_i^t represents the set of border OXC nodes within domain i and without loss of generality, it is assumed that these nodes are numbered as the first group of nodes in the domain, i.e., B_i^t = {v_i^1, ..., v_i^b_i}. 

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Meanwhile for multi-domain routing, a higher-level topology is defined containing the border OXC nodes and inter-domain links. This is given by a graph $H(U,E)$, where $U = \sum_i^n B_i$ is the set of border OXC nodes across all domains ($1 \leq i \leq D$) and $E = \sum_{i=1}^{D} \sum_{k=1}^{b_i^1} \sum_{m=1}^{b_i^m} E_{ikm}$ is the set of physical inter-domain links, i.e., $E_{ikm}$ interconnects $B_i^k$ in domain $i$ with $B_j^m$ in domain $j$. $1 \leq i, j \leq D$, $1 \leq k \leq b_i^1$, $1 \leq m \leq b_i^m$.

This graph contains all physical border nodes and inter-domain links but does not necessarily have full connectivity – which is achieved via appropriate topology abstractions (detailed next). Note that since DWDM networks are being treated, all links (physical, virtual) have associated binary wavelength availability vectors, i.e., $\mathbf{a}_{ij}^k$ is the wavelength availability vector for link $E_{ij}^k$, where $\mathbf{a}_{ij}^k(n) = 1$ if the $n$th wavelength is available and 0 otherwise, $1 \leq n \leq W$. Two different abstraction schemes are now presented.

**RESULT & DISCUSSION**

The multi-domain DWDM provisioning framework is tested using discrete event simulation using MATLAB SIMULATOR. An extensive GMPLS suite is developed and a 10-domain topology is tested. This network has good inter-domain connectivity, averaging 4.22 inter-domain links per domain (to stress inter-domain performance).
Simple Node and Full-Mesh Topology

All connections are generated between randomly selected domains using a 70/30 intra/inter-domain ratio.

Fig 4: Ten-domain Test Network Topology

First, Inter-domain light path blocking results are presented for all-optical networks, FIG.2. The differing abstractions are tested for MU and LU wavelength selection for W = 8 and 16 wavelengths (abstraction threshold Q = 2).
These results show best performance with the MU metric and concur with similar findings for single-domain networks Fig. 3. Shown is the blocking performance for optoelectronic domains which is tested for Q=2 and 10 wavelength converters per node (Q=2, MU selection). As expected, the carried load is higher (i.e., for an equivalent blocking probability) versus the all-optical case.

This is chosen to reflect practical networks which will likely field more intra-domain requests. Within a given domain, the OXC nodes are chosen randomly via a uniform distribution.
Finally, the inter-domain routing loads (LSA/sec) are shown for various all-optical and opto-electronic scenarios in FIG4 (i.e., LSA loads for inter-domain physical links and virtual links). Furthermore, intra/inter-domain routing timers (HT, HIT) are set to 10 sec and the SCF is set to 10%. All runs are averaged over 200,000 connections and mean holding times are set to 600 sec (exponential). Request inter-arrival times are also exponential and vary with loading. These paths are then searched for the maximum number of available wavelengths by performing a logical AND operation on all the binary available wavelengths vectors along the route links, yielding a path vector (Fig.3.13). Finally, these path-level availability vectors are summed and threshold by a level Q to obtain the final availability vector for the virtual link between the border nodes.

![Inter-domain routing LSA load (Q=2)](image)

These findings confirm a graded relationship between routing load and abstraction complexity, with full-mesh abstraction yielding almost four times higher load.

REFERENCES


