Designing Large-Scale ASTN-Based Optical Mesh Networks

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Abstract: *Automatically Switched Transport Network (ASTN) has many capabilities, such as dynamic connection/routing, that make it attractive for traffic engineering and optimization of next generation large scale optical mesh backbones. With increasing traffic demand spanning large geographic areas, optical mesh networks need to grow rapidly in terms of degree of meshing, bandwidth, and number of nodes. This translates (among others) into: (1) an increasing broadcast traffic and message load at each node in the ASTN control plane, especially during links or nodes failures, where dynamic route computation is required. Maintaining the stability of the routing protocol, and preserving service quality (restoration, network-wide delay, etc) as the mesh network grows larger becomes a key requirement, (2) significant memory, bandwidth and processing requirements to maintain and update network topology databases, and (3) additional operational considerations for connections availability, network latency, fault isolation, link maintenance and correlation of failures. This paper addresses the unique operational requirements in this type of large meshed networks environment and provides network designers with practical solutions to address scalability when building large ASTN-based mesh networks.*

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1. Introduction

Automatically Switched Transport Network (ASTN) is an emerging International Telecommunications Union (ITU) (G.ASTN, G.807) standard for intelligent optical networking, which provides a shift from traditional Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH) self-healing rings towards more flexible mesh architectures. Compared to dedicated 1+1 and shared protection ring schemes, restoration schemes based on shared protection mesh-topologies in networks with a high degree of connectivity can result in significant capacity savings, at the expense of generally-acceptable lower restoration times. For many service providers and carriers, the migration towards ASTN-based mesh backbone networks is very promising in terms of achieving higher connectivity, faster turn-up time, enhanced bandwidth utilization, dynamic ‘point-and-click’ connection provisioning, lower cost per managed bit and better network resilience.

The general ASTN architecture discussed in this paper is illustrated in Figure 1 and can be viewed as an IP-based optical connection control plane overlaid on top of an optical transport network. This general architecture constitutes the basis of next-generation optical transport networks. In Figure 1, the ASTN connection control plane is responsible to process user's request, and set up, or tear down the connections within the transport network. The optical transport network is the network that physically carries user’s traffic. As shown in Figure 1, the ASTN network is composed of multiple interconnected ASTN nodes, each made up of two main components: An Optical Connection Controller (OCC) and the Optical Cross-Connect (OXC). An optical cross-connect/switch has multiple ports and can switch multiple wavelength channels from an input port to an output port. The switching fabrics of these cross connects can be all-optical, electrical, or electro-optical.

The main two functions of the ASTN connection control plane are routing and signaling. Routing functions include topology discovery and maintenance, path computation and support for traffic engineering optimization. Efficient routing in the ASTN control plane can be performed by the Open Shortest Path First (OSPF) protocol which is being tailored to work within an optical framework. Signaling is carried out across various interfaces, including the User-Network Interface (UNI), the Internal Node-Network Interface (I-NNI), the Connection Control Interface (CCI), and the External Node-Network interface (E-NNI). Recall that the UNI is the interface that allows for example a client to signal for a connection to be setup or torn down, while the I-NNI links adjacent OCC nodes to each others, allowing the user’s request to propagate across the network. Similarly, the CCI is the interface between the OCC and the OXC and it is used for example to configure connections on the OXC and obtain information on its state, while the E-NNI is used to link different ASTN networks together.

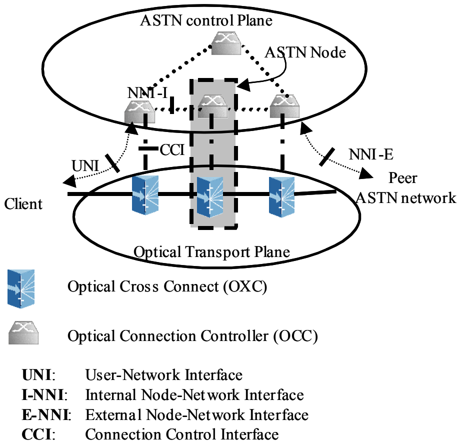

Figure 1. Simplified general ASTN architecture.

Signaling for light-path connections can be performed by the Generalized Multiple Protocol Label Switching (GMPLS) protocol, which is currently being defined in the Internet Engineering Task Force (IETF). If the path goes through several business domains, an Exterior Gateway Protocol (EGP) such as the Border Gateway Protocol (BGP) may be used for signaling. It should be noted that the ASTN signaling transport network across the internal and external NNIs can be logically (not necessarily physically) separated from the user data transport network, in which case the signaling will be referred to as being non-associated. Alternatively, when the signaling transport network is not separated from the user data transport network, we will refer to this type of signaling as being associated. An example of associated signaling is one that employs unused SONET/SDH overhead bytes to set up Synchronous Transport Signal/Virtual Container (STS/VC) connections.

ASTN-enabled mesh networks provide a range of protection and restoration levels, ranging from Layer 1 protection scheme, such as path-level 1+1 for highest-grade connection services down to unprotected pre-emptable schemes. Between these two, the ASTN controlled network offers a wide spectrum of restoration schemes, tailored to various service levels on a per-connection granularity for wider services offerings. Examples of such mesh restoration schemes include dynamic mesh restoration where the restoration path is computed at time of failure, and mesh path-level M:N where one or more restoration paths are selected from pre-computed routes at time of failure.

Though, most of the implementation issues related to ASTN-based optical mesh networks have been addressed by the ITU, IETF and other standard organizations, there are some prevailing issues that are still under investigation. For example, in [7], the importance of defining Service Level Agreements (SLAs) that are both tailored and adapted to the specific needs of optical mesh networks is highlighted. In [1], the authors addressed the unique challenges associated with end-to-end optical service provisioning and restoration in ASTN-based optical mesh networks. Some key control-plane challenges and considerations for all-optical and multi-domain ASTN optical mesh networks have been addressed in [5]; while the technological challenges and enabling solutions related to optical devices, subsystems, transmission technologies, and networking software are tackled in [8].

Yet, one of the most important prevailing design challenges in this type of optical mesh environments is to come up with network solutions that can scale-up to accommodate a large number of nodes and users, while providing acceptable restoration times. Motivated by this scalability requirement, this work is a first initiative that aims towards exploring the design's issues related to large-scale ASTN-based optical mesh networks and its main objectives are two folds:

1. It aims at identifying some of the operations considerations that need to be taken into account when designing large-scale optical mesh networks, of the type described above. The focus here is mainly on network scalability, which can be defined as the capability of the mesh network to deal with an increase in size, complexity, number of users and traffic without compromising existing functionality and flexibility.
2. The paper seeks to explore and compare the relative merits of the various options that can be envisaged to address some of the factors that can potentially influence the scalability of ASTN-based mesh networks.

This paper is organized as follows. Section 2 explores the main factors that influence the scalability of ASTN-based optical mesh networks. With these factors in mind, we move to section 3, whereby we explore some of the various options that network designers can consider to successfully address the scalability challenges when designing and planning for large ASTN-based mesh networks. We assess the pros and cons of each of these options and compare their relative merits. Finally, section 4 provides a summary of the main findings of the paper, as well as suggestions for further research.

2. Factors Influencing System Scalability in the ASTN-Based Mesh Network Environment

In this section, we identify some of the key factors that can potentially influence system scalability in the ASTN-based mesh network environment. Recommendations addressing some of these scalability considerations and allowing growth of the mesh networks will be discussed in section 3.

2.1. The Message Generation Rate under Various Fault Scenarios

Determining the maximum number of ASTN nodes that can co-exist in a single 'flat' area (i. e., with all nodes having the same peer-group level with no hierarchical structures) within the Optical layer control plane is closely tied to the message generation rate under various fault scenarios. This is also contingent on the (protocol-dependent) mechanisms, used for the dynamic discovery of resources and for dynamic path restoration. Under a fault scenario, as the number of nodes and links increases, so does the amount of distributed message exchange among the OCC nodes. This flood of message exchanges within the control plane can potentially consume significant memory, CPU and bandwidth.

2.2. The Critical Resources of the ASTN Routing Protocol

Memory, *Central Processing Unit (CPU)*, and *bandwidth* are the main critical resources of the ASTN-based routing protocol. For better scalability, consumption of these resources should expand less than linearly with network's growth. *Memory* is typically used for storing nodes' connectivity and topology information, as well as for storing OXC routing tables.

CPU requirement stems from the need to re-compute new routes and update routing tables, following topological changes, as well as from the need for I/O processing, required for handling all the routing update messages. The number of CPU cycles required to update routing tables is heavily dependent on the underlying protocol and on the size of the Optical Layer Control Plane. As the mesh network becomes large, the number of routing update messages that has to be processed, the number routes that need to be recomputed and the impact of topology change on routing tables increase; thus increasing CPU for route computation and for I/O processing requirements at the OCCs.

Bandwidth usage is the third critical resource that determines scalability of the ASTN Routing protocol. The amount of consumed bandwidth relies heavily on the routing protocol, and specifically on:

- Frequency of the updates (Periodic updates versus rush [flash] updates).
- Content of the updates (complete versus partial [delta] update of routing/topology information).
- Scope of the updates (targeting all OCCs in the optical layer control plane versus only those OCCs which are affected by the update in routing information).

Therefore, in addition to memory availability and processor capability, the efficient use of these two critical resources by the routing protocol plays a key role in defining the scalability in the ASTN-based mesh network.

2.3. Rapid Convergence of the Routing Protocol

In large meshed networks environment, the presence of multiple valid alternate paths adds new challenges for the convergence time of the ASTN routing protocol. In fact, in this type of large-scale networks, the ASTN routing protocol should maintain its ability to converge and propagate the changed route information, as network size (number of links/nodes) and traffic demands grow.

When links' status in the optical traffic plane becomes unstable, due to rapid intermittent faults, they can potentially result in a flood of port status update messages within the ASTN control plane. This oscillation scenario can consume significant critical resources in the ASTN control plane and prolong the convergence time of the routing protocol. Note that protection switching oscillations occur in multiple failure or degradation situations where one or more of the failures or degradations are intermittent. For example, oscillations could occur if a signal-degrade condition was detected on one optical line and an intermittent signal-fail condition was detected and cleared repeatedly (in the range of a few *msec*) on another line. It should also be noted that the convergence's completion of the routing protocol is not in the critical path of restoration, in the sense that it can take place at a slower rate.

2.4. The Amount of Traffic Being Carried by the Optical Backbone Network

Dense Wave Division Multiplexing (DWDM) is allowing unprecedented growth of bandwidth in the transport and optical domains, which covers growth in number of lambdas per fiber, and growth in bandwidth per lambda. Traffic growth implies that when a failure occurs in the optical traffic plane, following a link or an OXC node failure, the number of STS-N connections or lambdas that are affected and need to be re-routed to alternate paths gets larger. Similarly the numbers of connections or lambdas that may need to be pre-empted in order to re-establish higher priority services, under faults scenarios, get larger. From restoration and signaling perspective, a high degree of meshing, combined with a large amount of backbone traffic translates into more complex computations and processing delays during the dynamic end-to-end restoration of all STS-Ns or λs .

2.5. Total Protection Switch Time for Path-Level 1+1 Protected Services

Support for unidirectional 1+1 path switched services involves bridging (at the entry node) on any STS path signal on diverse routes through the opaque mesh network and selecting (at the exit node) the best of the two signals to drop from, based on the signal quality. At an exit node, the two received signals are both continuously monitored for path Loss of Pointer (LOP), path Alarm Indication Signal (AIS), Unequipped, Signal failure, path Defect Indicator, Signal degrade, and the best one is selected as the drop signal.

For path-level 1+1 protected services, the delay it takes for the failure indication to travel from the failed point to the destination node OXC needs to be taken into consideration, when seizing large mesh networks and this has previously been addressed in the contest of SONET Unidirectional Path Switched Ring (UPSR) [11]. Consider a path-level 1+1 protected connection that traverses a large number of 'pass-through' OXCs, before reaching the final destination. For convenience, we define the primary path as the current path being selected before the occurrence of a fault. When a failure occurs on the primary path, the relay OXC on the downstream direction (just after the failure) inserts P-AIS onto the affected channels, upon detection of the failure. Subsequent "pass-through" OXCs, along the primary path, relay the P-AIS, while the selector (at the destination-node) performs a protection switch, upon detection of P-AIS. Clearly, the total switch time for a given path (S_{wT}), defined as the time between the occurrence of the fault and the completion of the switch is the cumulative effect of:

- Defect detection and P-AIS generation time ($T_{G\text{-}AIS}$).
- P-AIS relay time at each 'pass-through' OXC (TR-AIS).
- P-AIS detection time at the end node OXC (TD-AIS).
- Path protection switch time at the selector of the end node OXC (TPS).
- Time for P-AIS to traverse fiber lengths in the direction of the end-node. This is dependent on the fiber propagation delay (T_d): ~5 msec/1000 Km.

For highest-grade Class of Service (CoS), this total time must be less than or equal to 60 ms.

By inspection, it can be shown that the worst case is due to failures on the link adjacent to the source OXC, as illustrated in Figure 2, below.

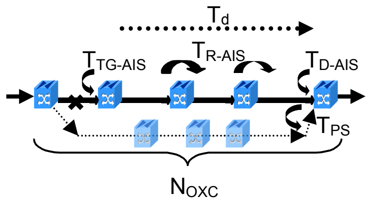

Figure 2. Worst-case path-level 1+1 failure scenario.

Let N_{OXC} denote the number of OXCs that are being used by a 1+1 primary connection. By inspection, and with reference to Figure 2 above, the total switch time for each path, under the worst-case scenario is readily obtained as follows:

$$S_{wT} = T_{G\text{-}AIS} + (N_{OXC} - 3).\ T_{R\text{-}AIS} + T_{D\text{-}AIS} + T_{PS} + T_d$$

Figure 3 shows the worst-case total switch time for each path versus number of tandem OXCs along the primary path, using the following typical [11] parameter values:

$$T_d = 20.0\ ms;\ T_{G\text{-}AIS} = 125\ \mu s;\ T_{R\text{-}AIS} = 125\ \mu s;$$
$$T_{D\text{-}AIS} = 375\ \mu s;\ T_{PS} = 20\ ms$$

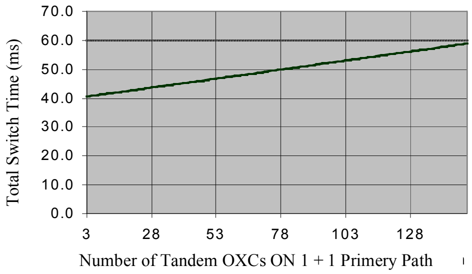

Figure 3. Worst-case total switch time versus number of OXCs along the primary path.

Note that in the above, our choice of 20 ms for T_d is based on the assumption of a fiber length of 4000 Km being traversed by P-AIS in the direction of the end-node. For transoceanic and transcontinental applications, it is expected that fiber propagation delay, T_d, will be the dominant factor in the worst-case total switch time equation. This is illustrated in Figure 4, where the worst case total switching time is plotted against fiber length, being traversed by P-AIS in the direction of the end-node, for various values of number of OXCs (Noxc) along the primary path. Note that these plots were obtained, using the same values for the equipment/hardware parameters ($T_{G\text{-}AIS}$; $T_{R\text{-}AIS}$; $T_{D\text{-}AIS}$; T_{PS}), specified above.

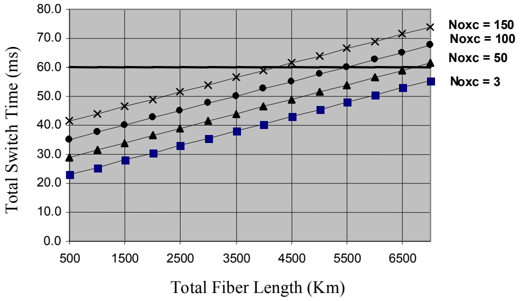

Figure 4. Worst-case total switch time versus total fiber length.

The results for the worst case switching time, would evidently change, depending on the equipment/hardware specific parameters ($T_{G\text{-}AIS}$; $T_{R\text{-}AIS}$; $T_{D\text{-}AIS}$; T_{PS}) and total fiber length. Nevertheless, depending on the equipment parameter values listed above, fiber length and number of hops, it might be advantageous to split long paths into sub-network protected sections in order to keep up with the total 60 ms switching time against fiber cuts.

2.6. Differential Delay for Path-Level 1+1 Protected Services

Path diversity induced by the implementation of path-level 1 + 1 protection schemes can potentially result in a differential delay between the primary and back-up paths. This is particularly the case if the primary and back-up paths exhibit differing characteristics, such as in the number of hops, and total fiber length. Differential delay can be a potential issue for the QoS of delay-sensitive services, such as voice, as the Service-Level Agreement (SLA) for the end-to-end delay should be met on both the primary path, as well as on the backup path, in case of a protection switching activity. Choice for the disjoint routes taken by the primary and secondary paths needs to take into account the minimization of the path differential delay.

2.7. Network's Survivability and Connections Availability

A mesh network's availability is not simple to determine, owing to general complexity and depending on the network physical topology, the working traffic demand matrix and on how restoration bandwidth is distributed throughout the network [6]. Let us first define network survivability and connection availability. Network survivability refers to the ability of a network to remain operational under a given set of predefined failure scenarios and restoration objectives (e. g., *x* % survivability with respect to all possible *double failure* scenarios within *y* ms restoration time). The survivability of a network consists of tallying up single and double failure statistics causing outage. The network failures are caused by cable cuts, supplier's equipment failures, service provider's procedural errors, act of nature, etc.

The survivability analysis represents one analytical tool to assess the general robustness or reliability of a network architectural option. Connection availability represents the probability that a particular service connection will be in service (out of service) at any given future time, e. g., *x* % uptime (downtime) for a service channel. The survivability analysis is usually an input to the availability analysis. A basic guideline is to have enough connectivity to at least recover all traffic as fast as possible from any single failure.

In order to explore the interplay between total link distance/adopted restoration scheme and connections' availability, we carried a combination of analytical and simulation studies (based on an internal network modeler and restoration simulation engine) on a representative network model composed of 7 nodes, 11 links, 11 connections and a total length of 8800 Km. Two approaches of restoration schemes were considered namely path-level 1+1 protection (protection path pre-configured) and dynamic path level restoration (restoration path calculated in real time after a failure occurs). For simplicity, it is assumed that all links have the same length of 800 km each. Further, we introduced the distance factor "K" to simulate the effect of increasing link distances, e. g., setting K = 2 implies a link distance of 1600 km. The key availability parameters that drive this model are listed in Table 1, below:

Table 1. Availability parameters.

Parameter	**Default Value**
Equipment Mean Time To Repair (MTTR)	3 hours
Cable cut rate	1cut/1000km/year
Cable cut MTTR	18 hours
Nodal failure rate (Act of Nature)	1 in a 1000
Nodal failure MTTR (Act of Nature)	24 hours

The analysis results for the sensitivity of the downtime to the "distance factor" *K* are shown in Figure 5, where: 1+1M and MPLR refer to mesh path-level 1+1 protection and mesh path-level restoration (dynamic path restoration), respectively. The unavailability is given in terms of average downtime per minute per year per connection. To simplify the computation of the downtime for the dynamic path restoration case, it was assumed that all "relevant" double failures would not be restorable.

It is readily observed from Figure 5 that irrespective of the restoration technique, the downtime increases as the total links length increases. In particular, for path-level 1+1 protected services in a large mesh network environment, as path lengths extend, each of the sides of the 1+1 paths becomes less available. In this case, the connections availability can be improved either by closing and opening protection at sub-network boundaries or by invoking the ASTN OCC controllers to redial (dynamically find) a second protection path, as soon as one of the two available 1+1 paths fails. Since opening protection at sub-network boundaries can create additional single point of failures, the second approach would be preferred.

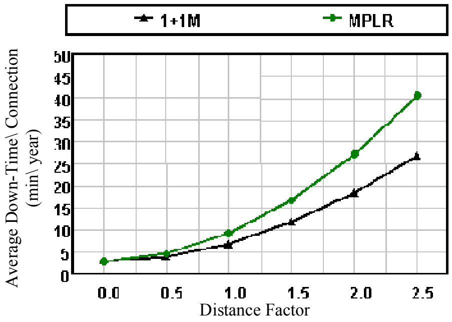

Figure 5. Average downtime versus distance factor.

3. Some Alternative Options to Address Scalability of Large Mesh Networks

In this section, we explore some of the various options that network designers can consider to successfully address the scalability challenge when designing and planning for large ASTN-based mesh networks. We assess the pros and cons of each of these options and compare their relative merits.

The obvious option to increase memory availability, bandwidth and processor capability (CPU) for the OCC nodes will not be elaborated thereafter. Discussions on these topics can be found in [9]. In addition, the use of event pipelining, as well as concurrent and parallel-distributed protocols in the ASTN control plane, as a means to address scalability are beyond the scope of this paper. For more details on the usage of system pipelining and concurrency for high performance design, the reader is referred to [3].

3.1. Associated Versus Non-Associated Signaling for Restoration

For shared back-up paths, signaling for restoration is required at both the reservation and the activation phase. While the reservation phase allows the establishment of the capacity of the back-up path, the activation phase activates this back-up path, after propagating the failure to the source OXC [10].

When back-up paths are shared, signaling for restoration in mesh networks is typically non-associated, in the sense that the signaling transport network is logically separated from the user data transport network. In large mesh networks environment, non-associated signaling for restoration might not be fast enough to guarantee quick restoration times. As a result, in-band associated signaling for restoration over SONET links can be envisaged, enabling restoration times of less than 200-300 ms. While the in-band associated signaling approach is generally faster than non-associated signaling, it has at least two main drawbacks: First, the proprietary usage of unused SONET/SDH overhead bytes to carry the signaling message does not favor inter-operability with other vendors OXCs, nor does it favor a graceful migration towards an all-optical network. Another limitation of associated signaling over unused SONET overhead bytes is the potential limited amount of signaling bandwidth that is made available.

3.2. Prioritization of Restoration Signaling in the ASTN Control Plane

To speed up signaling for restoration over the control plane, one can envisage the implementation of prioritization schemes in the ASTN control plane, based on some pre-defined Quality of Service (QoS) requirements. This can be achieved by implementing a non associated QoS managed signaling infrastructure overlay to allow high priority restoration messages cut through to source. Advanced GMPLS-based IP routing mechanisms such as DiffServ and Type of Service (ToS) can be used to implement such prioritization for restoration-type signaling.

3.3. Centralized Versus Distributed Restoration Processing in the ASTN Control Plane

In contrast to the distributed model where route computation of shared back-up paths is distributed among the various OCCs, one may envisage centralizing all the back-up path computations, for the purpose of end-to-end restoration in a centralized server. This centralized server has complete information regarding the mesh topology, bandwidth usage/availability, as well as end-to-end route details. A back-up server, synchronized to the primary server and operating in warm standby switchover can be allocated for redundancy. Under the centralized model, a client-server based protocol is used to re-route traffic, whereby clients residing at the OXCs will communicate to the central server for the reservation and activation of shared back-up paths.

While the main influencing scalability factor in the distributed restoration processing is how quickly changes are communicated sideways among the OCC controllers, the main limiting factor in the centralized restoration processing is how quickly remote changes find their way back to the remote server. For this reason, the centralized restoration model can become a real bottleneck in route computation after failures and thus it is not recommended. With the distributed restoration model, on the other hand, many simultaneous routing engines are working in concert and in parallel on behalf of the failed connections, associated with their source OCCs.

3.4. Protection Oscillation Control as a Means to Reduce Message Exchange Rates

In large mesh networks, it is desirable to prevent the OXCs from flooding the ASTN controllers with port status update messages, under multiple failure or degradation situations where one or more of the failures or degradations are intermittent. To this end, an oscillation control mechanism can be implemented at each OXC port to lock port-status toggling under sporadic Signal Fail (SF) or Signal Degrade (SD) conditions.

One method to limit the number of oscillations that could occur is to monitor how often an SF or SD condition is detected and cleared, and to uphold toggling if the condition is detected more than x times within a y seconds sliding window. After the port has locked on to the condition, it would consider the port to be in an SF or SD condition for duration of *y* seconds. The port will not unlock to the SF or SD condition until that condition is cleared and a maximum of *w* toggles ($w < x$) have occurred within the last y seconds sliding window.

3.5. Heuristic Routing Algorithms for Restoration Time and Processing Efficiency

With dynamic path mesh restoration, the restoration path for some services can be computed at time of failure, with the optical controllers working in concert to automatically re-establish the connection over the optimal path. In large mesh networks, with numerous valid alternate paths, convergence to the optimal path may require large memory and processing requirements and my not be completed within the SLA guaranteed restoration time. As a result, one may consider implementing distributed heuristic constrain-based routing algorithms to seek a fast sub-optimum path solution when multiple valid alternative routes are available [4].

3.6. Partitioning Large ASTN Control Planes into Sub-networks

In order to scale the ASTN-based dynamic path mesh restoration protocols to accommodate hundreds or thousands of optical cross-connects, some partitioning of the ASTN control plane might be required, as illustrated in Figure 6. Under this model, the ASTN control plane is divided into smaller sub-networks, where OCC nodes in the ASTN Control Plane exchange messages only with those peer OCC nodes, located in the same sub-network [2].

The advantage of the above model resides in the fact that the routing information and topology details of one sub-network are not available to any other sub-network. In other words, OCC nodes within a particular sub-network are not required to maintain routing information for nodes located outside their area. This has the effect of confining the scope of messages' broadcast to a manageable size within each sub-network, enabling better scalability of the ASTN routing protocol.

Existing protocols may be suitably enhanced to enable the dynamic provisioning and restoration of end-to-end connections across multiple I-NNI sub-networks. In particular, if the 'source' and 'destination' OCC nodes for a given path are located in different sub-networks, then adjacent border OCC nodes in each sub-network along the route will act as Gateways for path restoration on behalf of the original source-destination nodes. Note that the Gateway OCC nodes will have more stringent processing requirements than the remaining OCC nodes and that some form of summarization is required to minimize the information being exchanged by the Gateway protocol. Finally to route optimize across various sub-networks and domains, a hierarchical overlay model may be required.

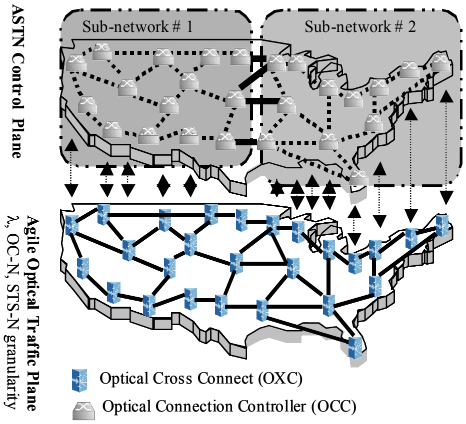

Figure 6. Subnetwork-based routing in large optical mesh networks.

4. Conclusions

ASTN-based Optical mesh networks are expected to grow rapidly, in terms of higher meshing, more traffic and larger number of nodes, spanning large geographical areas. This raises some scalability concerns, especially under fault scenarios. In this paper we identified some of the key factors that can potentially influence the scalability of these mesh networks. We have explored and compared the relative merits of the various options that can be envisaged to address some of these scalability factors.

The main conclusions that can be drawn from this paper are as follows:

- The use of layer 1 protection mechanisms to provide high-grade connection services is a necessary part of the capabilities of a connection control system.
- Path-level 1+1 protection scheme makes it possible to achieve sub-60 ms switching, on a per path level. Further, for mesh networks spanning large geographic areas, fiber propagation delay becomes the main influencing factor on the total path-level 1+1 protection switch time. In this case, it might be advantageous to split long paths into sub-network protected sections.
- For path-level 1+1 protection and dynamic path restoration techniques, the average downtime per connection per year increases as the total links length increases. In particular, for the path level 1+1 case, connections availability can be effectively enhanced by invoking the ASTN OCC controllers to dynamically find a second protection path, as soon as one of the two available 1+1 paths fails
- In large mesh networks environment, distributed restoration mechanisms lead to a large amount of signaling traffic, but scale and perform better than centralized models. In conjunction with this, a non-

associated QoS managed signaling infrastructure overlay is recommended to allow high priority restoration messages cut through to source.

- Large ASTN control planes need to be divided into sub-networks. Routing and topology details should not be passed among sub-networks. In addition, optimization across various sub-networks may require a hierarchical overlay.

Finally, simulation studies of the performance of large scale mesh networks under various failure scenarios are left for future investigations. Such studies can provide useful insights into the maximum number of OCC nodes, links and (service) connections that can be supported, without compromising existing functionalities and flexibility.

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