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MASTER THESIS

TITLE: Investigation on PCE-based multi-domain optical networks

MASTER DEGREE: Master in Science in Telecommunication Engineering & Management

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Overview

The last decade has seen many advances in high-speed networking technologies. However, many issues are still open for the development of next generation optical transport networks in order to optimize the resources; this is especially true in the context of multi-domain optical networks. In this context, the IETF entity introduces the Path Computation Elements (PCE) module to improve the network resources occupation.

In multi-domain networks, each network domain is usually owned by a different operator/administrator and it entails the reluctant behavior from some operators concerning the dissemination of intra-domain information.
The purpose of this work is to present and compare different Traffic Engineering (TE) information dissemination strategies between PCEs in multi-domain optical networks. In such network context, recent studies have found that path computation only with local domain visibility yields poor network performance. Accordingly, certain visibility between domains seems necessary. Aiming to fit the confidentiality requirements of the composing domains and to improve the final network blocking probability, novel link aggregation techniques have been proposed. These techniques summarize the state of network domains resources efficiently. Besides, this aggregated link information is afterwards disseminated to all the remainder domains in the network. In order to fulfill this requirement, we introduce different update triggering policies to make a good trade-off between routing information scalability and inaccuracy. On the other hand, the IETF entity has defined several mechanisms (BRPC and H-PCE) for establishing inter-domain paths to compute routes through cooperation between PCEs.

This master thesis proposes a hybrid path computation procedure based on the H-PCE and BRPC. It is important to highlight that the performance of all contributions has been supported by illustrative simulation results.

INDEX

GLOSSARY

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AP	Allocated Path
AS	Autonomous Systems
ASON	Automatically Switched Optical Network
ATM	Asynchronous Transfer Mode
BGP	Border Gateway Protocol
BPC	Blocked Path Counter
BRPC	Backward Recursive PCE-based Computation
BTP	Blocking Probability Threshold
CC	Connection Controller
DWDM	Dense Wavelength Division Multiplexing
E2E	End-to-End
EGP	Exterior Gateway Protocol
EMS	Element Management System
E-NNI	Exterior Network-Network Interface
ER	Explicit Route
GMPLS	Generalized Multiprotocol Label Switching
HPC	Hybrid Path Computation
H-PCE	Hierarchical Path Computation Element
HT	Hold-down Time
IDTP	Inter-Domain Transit Path
IDTP-CCB	Inter-Domain Transit Path – Common Cost Balancing
IETF	Internet Engineering Task Force
IGP	Interior Gateway Protocols

I-NNI	Interior Network-Network Interface
IP	Internet Protocol
IPTV	Internet Protocol TeleVision
ITU-T	International Telecommunication Union Telecommunication Standardization Sector
LMP	Link Management Protocol
LRM	Link Resource Manager
LSA	Link-State Advertisement
LSP	Label Switched Path
ND	Nodal Degree
NGN	Next Generation Networks
NMS	Network Management System
NNI	Network-Network Interface
OADM	Optical Add-Drop Multiplexer
OCC	Optical Connection Controller
OIF	Optical Internetworking Forum
OMS	Optical Multiplex Section
OSPF-TE	Open Shortest Path First - Traffic Engineering
OTN	Optical Transport Network
OTS	Optical Transmission Section
OUT	Optical Transport Unit
OXC	Optical Cross Connect
PCC	Path Computation Client
PCE	Path Computation Element
PCEP	Path Computation Element Protocol

QoS	Quality of Service
RC	Routing Controller
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RSV P-TE	Resource Reservation Protocol - Traffic Engineering
SB	Static Balancing
SDH	Synchronous Digital Hierarchy
SONET	Synchronous Optical NETworking
TA	Topology Aggregation
TDM	Time-Division Multiplexing
TE	Traffic Engineering
TED	Traffic Engineering Database
UNI	User-Network Interface
VoD	Video on Demand
VSPT	Virtual Shortest Path Tree

1. INTRODUCTION

The continued growth of Internet traffic as well as new multimedia services has created the need to design more powerful, robust, secure and scalable networks. In addition, these new services mean that new requirements should be taken into account when proposing alternatives. Consequently, the existing telecommunications network should evolve to match the shift that is occurring in the traditional voice network towards data-centric infrastructure.

The transformation of the existing transport networks is caused largely by new broadband services offered by operators. These include the triple play services, comprising, in a single package, Video services (VoD and IPTV), Voice and Internet, and services for online games. Other remarkable factor of this change is the growing demand of bandwidth’s capacity from sectors as business, public organizations, health and science.

The IP traffic explosion in the recent years has entailed a restructuring of the network architecture, as a consequence of this exponential growth that has reached unsustainable limits in terms of capacity. As a result, future trends and changes are shaping the transmission of next generation.

Optical networks represent the basic level of transport, whatever the technology used in data switching. Similarly, IP has become the facto standard technology for the development of services. Between the two layers, a number of technologies such as SONET/SDH, provide the interface between IP layer and optical layer. The advantages obtained from the removal of these intermediate levels Figure 1.1, passing it to IP functionality, or to optical equipment, are the following:

- Simpler network architecture.
- Less equipment and therefore more scalable and much cheaper to operate.
- Reduction of the number of technologies that operators must know and significantly reduces the number of elements that can fail.
- Reduces the complexity in the provision, operation and network planning to minimize the operating costs of providing services and maximize profits.

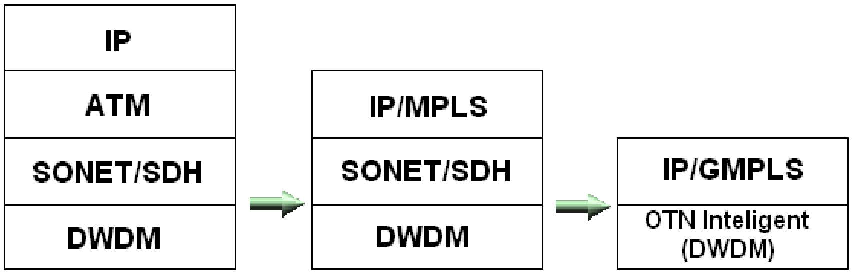

Figure 1.1 Reduction of layers

The SONET/SDH layer tends to be removed, transforming the backbone in a two layers network. Therefore, failure detection and restoration of the network becomes critical tasks. Besides, the increase in transport efficiency also reduces the number of mechanisms to use, since it reduces the number of layers. In the step that eliminates the intermediate layer SONET/SDH, global restoration mechanisms should be implemented in the optical or IP layer. This implies the need to replace SONET/SDH nodes with optical nodes, in which the switching is performed transparently at the optical level (OXC and OADM). This converges to a new generation of networks.

The following chapter explains in detail the composition of the optical network, the functions and the involved entities that regulate these networks.
Chapter3 explains the multi-domain path establishment problem and explain some protocols proposed by IETF entity to optimize the path establishment in optical networks. Chapter 4 and 5 describes the proposals solutions to improve protocols described in chapter 3. The rest of the thesis is divided into chapter 6, which defines the conditions that have been implemented in order to test the protocols described in chapters 4 and 5. Chapter 7 focuses on the final results and finally the conclusions are highlighted.

2. ASON/GMPLS NETWORKS

This chapter explains the parts of an ASON network, its operation and GMPLS protocols for the control plane to optimize resources.

2.1. ASON architecture

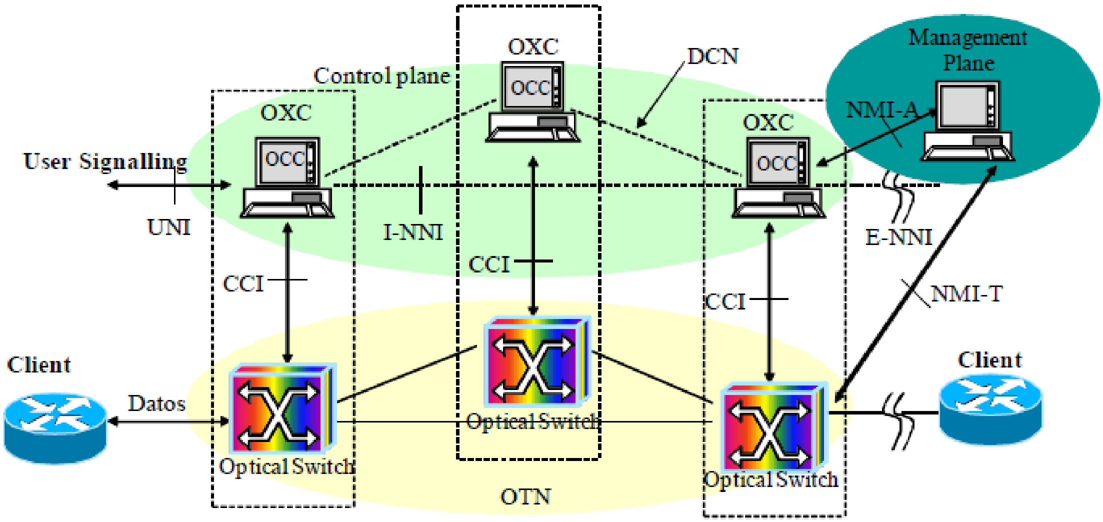

Figure 2.1 ASON architecture [1]

Figure 1.1 shows the ASON network architecture defined by ITU-T in G.8080/Y.1304 [1]. It can distinguish three parts:

- Transport Plane: is composed by an Optical Transport Network (OTN) that provides reconfigurable end-to-end optical connections (unidirectional and bidirectional). It must also detect information about the state of connections (failures, signal quality, etc).
- Control Plane: Dynamic establishment/elimination of optical connections requested from the user domain (switched connections) or the Network Management System, NMS (soft-permanent connections).
- Management Plane: management functions in both control and transport planes.

The interfaces between planes are:

- E-NNI: end-to-end service activation, multi-vendor inter-working and independence of survivability.

- I-NNI: Intra-domain connections establishment and explicit connection operations on individual switches.

- UNI: Client driven end-to-end service activation, multi-vendor inter-working, multi-client, multi-service and service monitoring interface.

2.1.1 Optical Transport Network (OTN)

OTN has been standardized by ITU-T. The basic definition of the OTN layers model architecture is on G.872 [3]. This is the standard to transport wavelengths in DWDM transparent networks.

G.872 is formed by three sub-layers which provide OAM functionalities:

- Optical Channel (Och): manage optical channels which transport different client signals.

- Optical Multiplex Section (OMS): manage multiplexed optical signals.

- Optical Transmission Section (OTS): manage the transmission of optical signal over fibres.

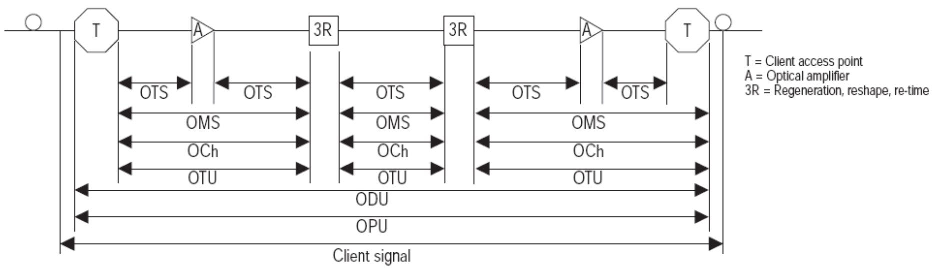

Figure 2.2 G.872 divisions in layers [30]

The definition of the interfaces (sub-layers of Optical Channel and OTU frame formant) is on G.709/Y.1331 [2].
These sub-layers are: Optical channel Transport Unit (OTU) that adapt the client signals, Optical channel Data Unit (ODU) monitoring connections end-to-end and Optical channel Payload Unit (OPU) monitoring of the signals between regeneration points. Next figure shows the heading between these sub-layers.

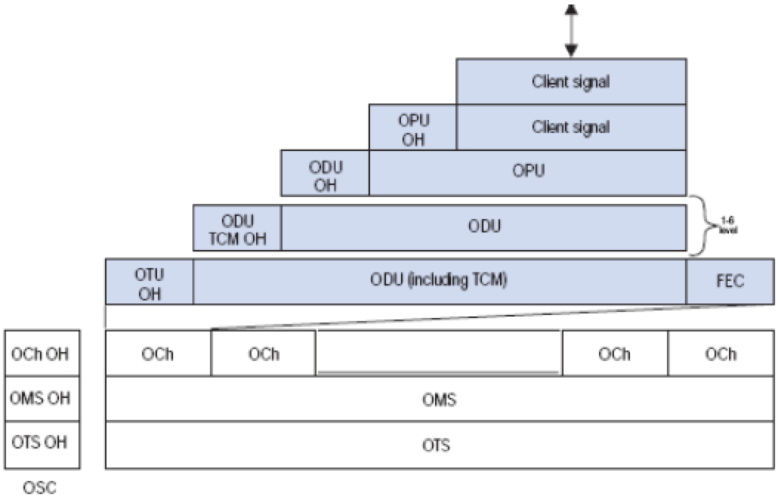

Figure 2.3 Signal clients mapping [30]

The frame OTU allows to transport different technologies in a single frame as shown in the following figure. The optical channel transport unit 1 (OTU1) has a bit rate 2,666,057.143 kbit/s and OTU2 10,709,225.316 kbit/s. Figure below shows an example of technologies can be introduced into an OTU container.

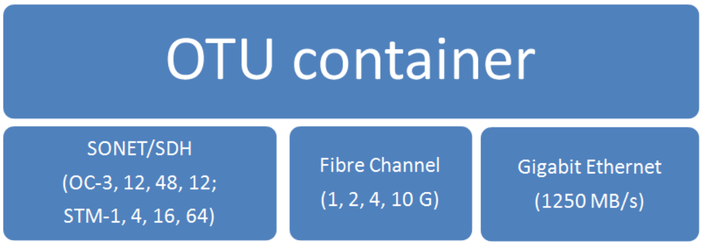

Figure 2.4 OTU container example

2.1.2 Management Plane

This plane is based on tools implemented to help network administrators to control and maintenance of the networks; it may be queried by network administrators, users, and other planes. The key functions identified for this plane to provide end-to-end services are:

- Monitoring: Network element status, errors, network utilization and configurations.

- Troubleshooting procedures: Investigation of issues and problems in the network.

- Management plane status: Maintenance management plane state and restoration mechanisms running after failure.

The management plane may be divided into two functional blocks, Management System Element (EMS) and Network Management System (NMS). EMS manages network elements (OADM, ROADM, OXC, etc.). All EMSs are connected to the NMS across Network Management Interface (NMI) and have a global vision of the network.

This plane is ready for static traffic, which to be a high rate of dynamic traffic; the management plane cannot establish all connections. This implies a non-optimal utilization of the network resources. In order to manage the establishment of dynamic traffic, there is the control plane.

2.1.3 Control Plane

The principal's objectives of Control plane are provisioning multi-vendor / multi-carrier interoperability and ensure end-to-end service provisioning with high availability. Control plane is required because it produces an efficient management of the resources, discover automatically neighbours and resources. Disseminate the global topology: links, switching nodes, etc. And provide dynamic bandwidth requesting to establish connections, route calculation, connection establishment and efficient management of connections.

Each Transport plane node has a related control plane node named Optical Connection Controller (OCC). All OCC's are interconnected by data communication network.
OCC is responsible to disseminate network topology and optical resources using routing protocols. OCC manages reservation and provisioning optical connections using signaling protocols.
Next figure shows the different blocks of OCC composition.

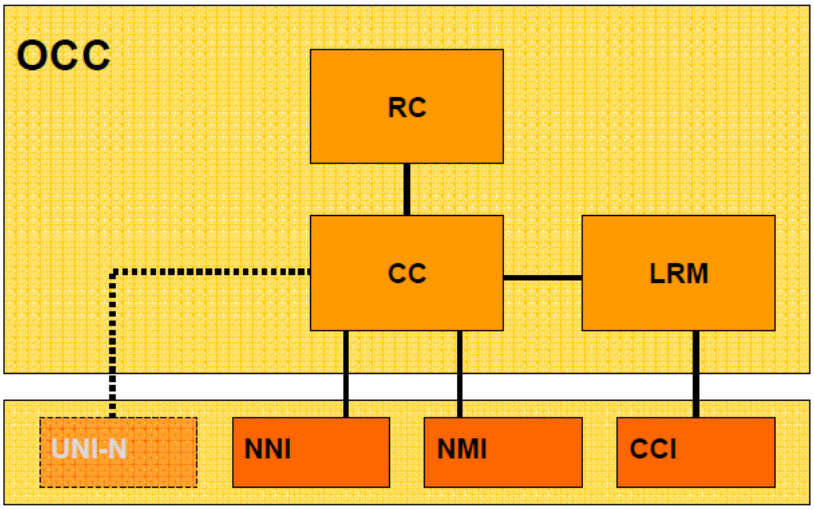

Figure 2.5 Control plane functional modules

The basic modules of the control plane are:

- Link Resource Manager (LRM): Responsible for Control plane local link connection inventory. Resources provided through configuration or discovery. Receives request for resources from Connection Controller. And provides information to Routing to facilitate topology advertisements.

- Connection Controller (CC): Responsible for establishing connections across a domain. Requests route to use from Routing Controller and requests specific local link resources from LRM.

- Routing Controller (RC): Responsible for providing paths between two points in the network. Maintains topology view and the paths are calculated to meet service constraints.

To implement Control Plane several protocols have been defined. These are shown in the following subchapter.

2.1.4 GMPLS protocols

This subsection explains the GMPLS basic protocols: LMP [4], OSPF-TE [5] and RSVP-TE [6].

TE [7] is concerned with performance and resources optimization in response to dynamic traffic demands and node or link failures. It is the process of mapping traffic demand in to a network.

2.1.4.1 Link Management Protocol (LMP)

This protocol has four functionalities. First of all is Control Channels Management. It allows maintaining control channels connectivity between neighbours. The other three functionalities are Link Property Correlation, Link Connectivity Verification and Fault Management.

2.1.4.2 Open Shortest Path First-Traffic Engineering (OSPF-TE)

OSPF-TE is described in RFC 3630 and has two main functionalities: resource discovery and calculate routes.

This protocol collects information from all nodes in the own domain and interchanges topology information whit others domains using Opaque Link State Advertisements (LSA) carrying Type Length Value (TLV). Opaque LSA is defined in RFC 5250 [10]. There are eleven types of LSAs, but OSPF-TE only uses types 9, 10 and 11. When you have gathered all necessary information, this protocol provides the shortest route through the Dijkstra's algorithm [18].

On the other hand, is capable of detecting changes in the topology, such as a broken link. Once you know the link protocol failed, quickly generates a new tree of resources to establish new paths.

If no wavelength converters exist in the network, these must accomplish the wavelength continuity constraint (all-optical networks).

2.1.4.3 Resource ReserVation Protocol-Traffic Engineering (RSVP-TE)

RSVP-TE is a protocol of transport layer designed to reserve network resources and establish label switched paths (LSP’s RFC 4206 [20]). The main features are: Resources calls for unidirectional and bidirectional links. This protocol has several types of message, but the most important messages are Path and RESV.

OSPF-TE protocol collect all the necessary information and selected the explicit route (intra-domain path) or no explicit route (inter-domain path whit one or more loose hops). IETF also introduce Explicit Route Object (ERO) [28] that contains the route marking the loose hops. Each loose hop is because the operator does not provide physical information about its topology. Thereby receiving a request to cross its domain, operator calculates the shortest route that crosses his domain and responds with a cost. This operator stores a connection identifier with the path you just calculated. This identifier is the Path Key identifier [27].

Once the ERO is collected RSVP-TE protocol sends a message source to destination (Path) through the nodes that make up the ERO. Each node (intra-domain path) or operator (inter-domain path) is responsible for making the resource reservation. Then when operator receives the message, it tries to book the resources they had calculated whit the Path Key. Once you have successfully reserved the resources, destination node sends RESV message to source node confirming the resource reservation and finally, source node send the path to destination node.

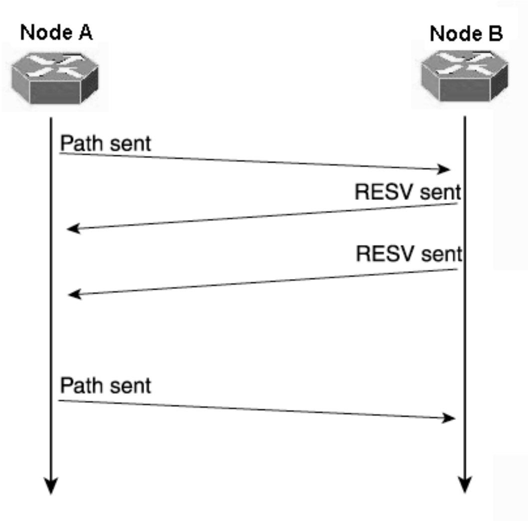

Figure 2.6 RSVP-TE example

2.1.5 PCE-based Control Plane

Research efforts related to optical transport network infrastructures, have been mainly focused on single-domain scenarios, where scalability and confidentiality do not represent an issue. However, the future optical networks will include several domains, each controlled by a different service provider/network operator. From the routing perspective, a domain is a collection of network elements within a common address management or path computational responsibility, namely, an Interior Gateway Protocol (IGP) area or an Autonomous System (AS) [17]. In such scenario, the computation of end-to-end paths poses new challenges and traffic engineering solutions addressing the constraints imposed by scalability, domain information confidentiality, heterogeneous transmission technologies and physical layer impairments, must be provided. Due to the limited availability of effective solutions, TE is practically unavailable in multi-domain optical networks. The topological information exchange between domains is normally reduced to the minimum, only spanning the shared links and border nodes information. The lack of topological information related to neighbouring domains hinders the routing entities' capacity to compute inter-domain end-to-end paths efficiently. Therefore, the solution provided by IETF is the Path Computation Element (PCE) [13] to add to the control plane.

This element is an entity that is capable of computing a network path based on a graph. PCE would be able to compute the path of a TE LSP by operating on the TED and considering bandwidth and other constraints applicable to the TE LSP service request.

The idea of this element is likely to have a global vision of the network even in abstract mode. As operators want to exchange the minimum amount of information on resources, there are abstractions of networks to limit the flow of information between domains.

The main features of PCE are:

- Path computation is applicable in intra-domain, inter-domain and inter-layer contexts.

- You can use one or more PCEs to establish a path in one domain.

- The PCE may or may not be located at the source-destination of the path.

- The computed path by PCE may be an explicit path or a strict/loose path, where a loose hop refers a loose of information between nodes (for example, virtual link).

- PCE-based path computation model can be used in conjunction with other path computation models.

Next figure shows a PCE that is external to the requesting network element. It shows an inter-domain connection where source node request to other domain node. PCE can initiate signaling to establish the service; it makes a request to the external PCE. The PCE uses the TED and returns a response.

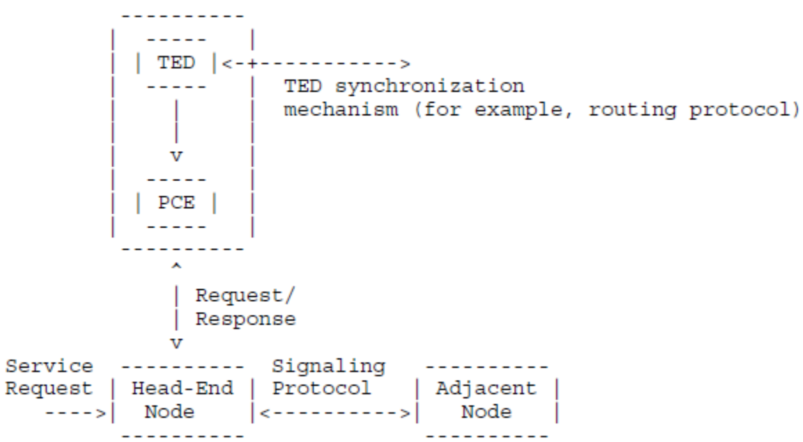

Figure 2.7 External PCE node [16]

On the other hand, management plane can also use the PCE. In the following figure, NMS supplies the source node with a fully computed explicit path for the LSP that it is to establish through signaling. The NMS uses a mechanism of management plane to send this request. The NMS constructs the explicit path using information provided by the operator. It consults PCE which returns a path for the NMS to use.

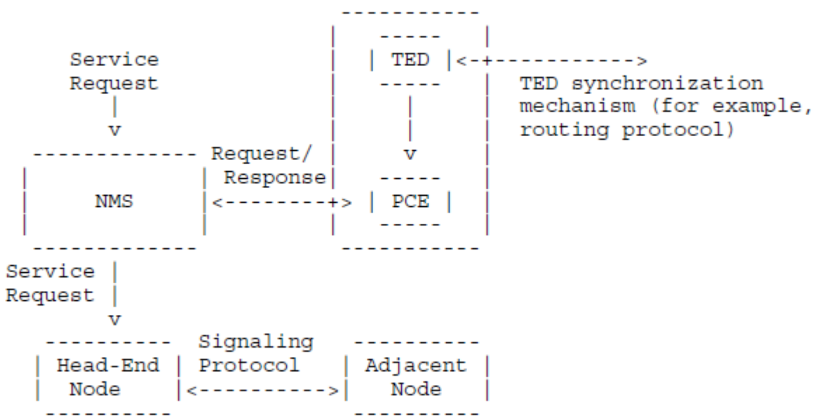

Figure 2.8 Management-based PCE usage [16]

To establish communication between the IETF's PCE introduces the PCEP protocol [13].

2.1.5.1. PCEP

When a client requests a connection it does so by PCC (Path Computation Client). But who is responsible for establishing the route is the PCE module. Therefore the need arises to establish a communication protocol between PCC-PCE and PCE-PCE. This protocol is PCEP and is described in RFC 5440 [13]. Several PCEP messages are defined:

- Open and Keep-alive messages: to initiate and maintain PCEP session.
- PCReq: its send when a PCC request a path computation to PCE.
- PCRep: its send when a PCRep message can contain either a computed path if the request can be satisfied, or a negative reply if not.
- PCErr: to communicate an error.
- Close message: to close PCEP session.

2.2. Standardization entities

All standards were developed by three entities:

- ITU-T (International Telecommunication Union) [25]: Has defined requirements but not protocol at this point.

- IETF (Internet Engineering Task Force) [23]: Has begun work through analysis of ASON requirements and evaluation of existing routing protocols. It is the entity responsible for publishing the draft of researchers if they deem it appropriate and turn them into RFC's. Some initial proposals for extensions are in progress.

- OIF (Optical Internetworking Forum) [24]: Has developed and tested prototype extensions to meet ASON requirements, for example defining optical interfacing protocols (UNI, NNI). Working with IETF / ITU-T to extend the standards. Recently the OIF has also detailed routing and signaling functionalities for E-NNI. Specifically, a hierarchical routing based on OSPF-TE routing protocol.

To standardize the protocols these entities cooperate. For example, for signaling process, three entities cooperate but to routing process only cooperates ITU-T and IETF.

Figure 2.9 Standardization entities

3. MULTI-DOMAIN PATH ESTABLISHMENT

This chapter explains some solutions to establish an inter-domain LSPs. Furthermore topology aggregation schemes are exposed for connection establishment mechanisms use.

To address multi-domain path establishment problem, the Internet Engineering Task Force (IETF) and the Optical Internetworking Forum (OIF) standardization bodies have proposed both architectural and protocol specifications to facilitate the interoperability amid different network domains, technologies and vendor equipments. Specifically, referring to IETF and Path Computation Element (PCE)-based solutions, path computation strategies are described in sub-section 3.2 can be seen main important mechanisms to establish LSP.

In the following sub-chapter explains the different types of abstract topology to exchange information between domains

3.1. Topology aggregation

Recent studies have analyzed three topology abstraction schemes for multi-domain optical networks, that is, *simple node*, *symmetric-star* and *full-mesh* [8], [9]. The following figure shows an example optical network. Figures 3.2, 3.3 and 3.4 had shown the abstractions of the optical network.

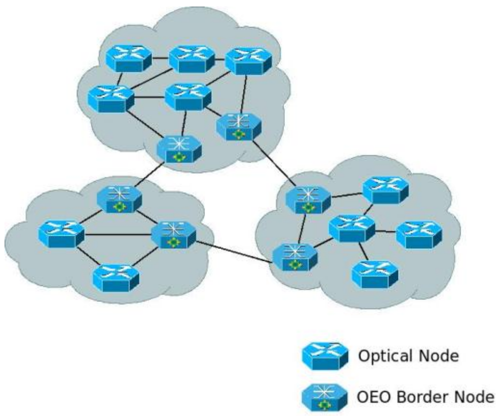

Figure 3.1 Optical network example

3.1.1. Simple node

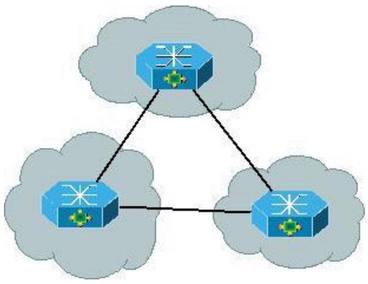

Figure 3.2 Simple node topology abstraction

This is the simplest of all the abstraction schemes and condenses a domain into a single virtual node emanating all physical inter-domain links. For example, the three border nodes in domain 2 in Figure 3.1 are simply collapsed into a single virtual node with 3 inter-domain links. This scheme provides no visibility into domain internal state and has low inter-domain routing overheads.

3.1.2. Full-mesh

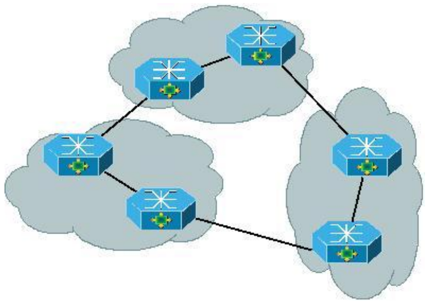

Figure 3.3 Full-mesh topology abstraction

This abstraction is that a major share information on their own domain to the other domains. It is composed of all border nodes interconnected with each other. Each interconnection between border nodes is a virtual link. The cost of using this virtual link is proportional to the actual structure. The full-mesh scheme is designed to perform intra-domain state summarization.

3.1.3. Symmetric-star

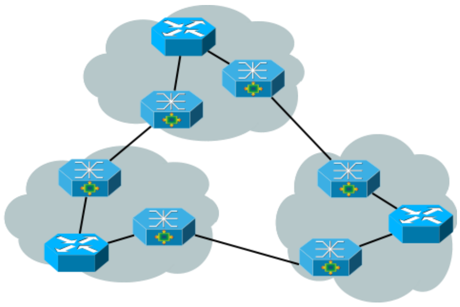

Figure 3.4 Symmetric-star topology abstraction

Symmetric-star is an intermediate abstraction between simple and full-mesh. This abstraction not shares much information about its structure as full-mesh but shares more than simple node. Show all border nodes, but no direct connections between them. Shows an intermediate node through which all border nodes are interconnected.

The status of these abstractions is disseminated between domains by the signaling protocol OSPF-TE [5]. All this information is collected in the Traffic Engineering Database (TED) and the PCE accessed to establish the connection.

3.2. Path-setting mechanisms

In order to solve the problem have identified several mechanisms to establish connections. First, the IETF defined a model in which the PCEs not cooperating between them (Per-domain path computation). Then IETF introduced mechanisms that PCEs cooperates and greatly improves the results of the Per-domain procedure. And finally this master thesis is unfocused to improve this results whit chapter 4 (source routing computation) and chapter 5 (HPC).

3.2.1. Non cooperation between PCEs

This subsection briefly explains Per-domain path computation method that is defined in [17].

In this mechanism, PCEs don’t collaborate between them. Source PCE don’t has knowledge of the sequence of domains that the path has to perform. Every

PCE have a routing table in which border node decides that its signal goes according to the destination domain. So each domain is aware of its internal resources and inter-links that connect their border nodes to the other domains. Because of this lack of information are very easy path that cannot be established and this leads to high blocking probability. To improve the blocking probability IETF introduce the concept of Crankback signaling [30]. Basically is that if at the time of reservation resources using RSVP-TE a link fails, then turns back to try to find another way.

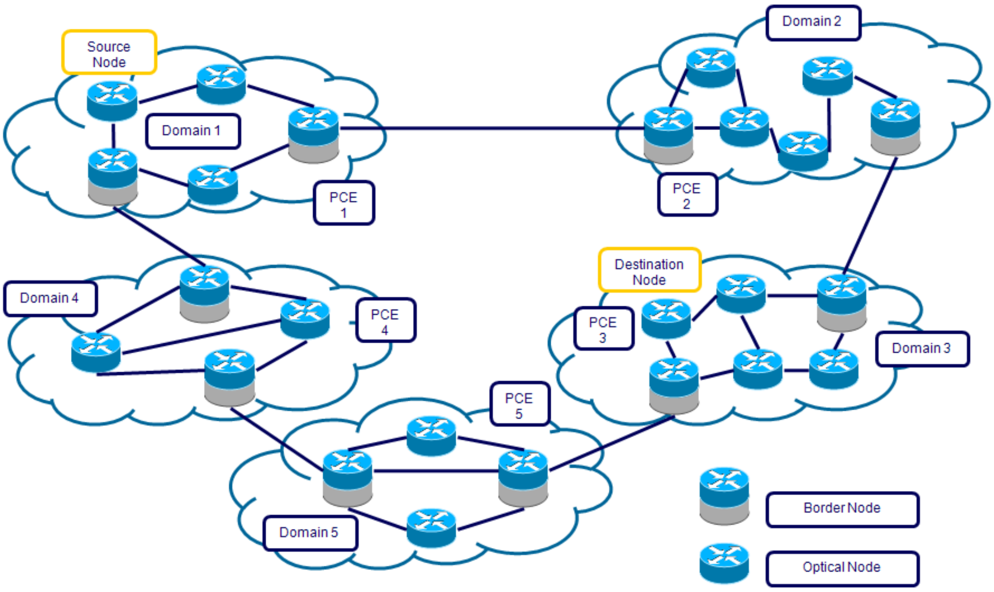

Figure 3.5 Network example

An example of the connection establishment process is:

- PCE 1 does not know where the destination is, but knows that for go to domain 3 signal needs to cross domain 2 because there is in his routing table.
- PCE 1 sends RSVP-TE to PCE 2 requesting the path to PCE 3.
- As PCE 2 is neighbor PCE 3, it sends request to PCE 3
- PCE 3 checks availability and send the response message to PCE 1 notify that the resources are reserved.
- PCE 1 starts to allocate the end-to-end path.

3.2.2. Cooperation between PCEs

There are several modes of communication between PCEs. On one hand, Figure 3.6 shows an example of PCE communication. Each PCE have a bidirectional connection whit all PCEs. This application is used by some computational methods, for example, BRPC or source routing computation. On the other hand, Figure 3.7 displays a hierarchical PCEs bidirectional communication. This architecture is used basically in H-PCE computational method.

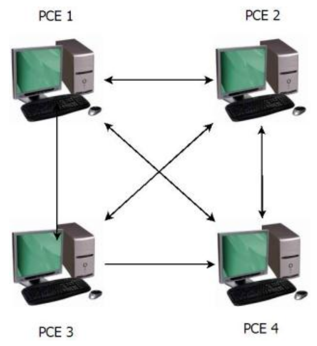

Figure 3.6 PCE communication example

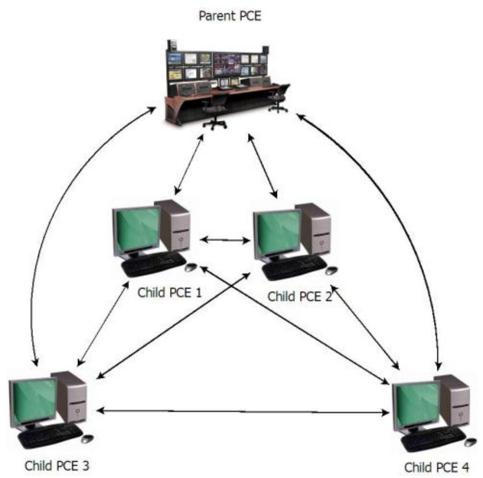

Figure 3.7 Hierarchical PCE communication example

This subsection describes mechanisms proposed by IETF (BRPC and H-PCE).

3.2.2.1. Backward Recursive PCE-based Computation

The IETF has also introduced the BRPC procedure [11] as collaboration between PCE's to improve per-domain path computation results. This protocol is based on the Path Computation Element Protocol (PCEP) [13].

This procedure relies on communication between cooperating PCEs. In particular, the PCC sends a PCReq to a PCE in its domain. Once the PCE knows destination domain, through pre-established sequence forward the request between PCEs, domain-by-domain until the PCE responsible for the domain containing the LSP destination is reached. The PCE in the destination domain creates a tree of potential paths to the destination (the Virtual Shortest Path Tree - VSPT) and passes this back to the previous PCE in a PCRep. Each PCE in turn adds to the VSPT and passes it back until the PCE in the source domain uses the VSPT to compute an end-to-end path that it sends to the PCC. And now PCC starts the signalling (RSVP-TE) in order to allocate the path.

Following figure shows an example of an optical network to explain an example of BRPC procedure.

The connection is established (Figure 3.5) through the following steps:

- The PCC (source node) wants to calculate a inter-domain route until the destination node. PCC sends a PCReq to a PCE in its domain (PCE 1) requesting an end-to-end path computation.

- The request is forwarded between PCEs, domain-by-domain, until the PCE responsible for the domain containing the LSP destination is reached. A PCReq is forwarded using the domain path 1-2-3.

- The PCE in the destination domain (PCE 3) creates a tree of potential paths (the Virtual Shortest Path Tree VSPT) from their border nodes connected to the upstream domain and the destination node. After that, PCE 3 passes this VSPT back to the previous PCE in the domain path (PCE 2) using a PCRep.

- PCE 2 in turn adds to the VSPT its potential paths between border nodes and passes it back to the next PCE in the domain sequence. This procedure is repeated until the source domain PCE is reached.

- PCE 1 uses the collected VSPT to select an end-to-end path. Then, PCE 1 sends to the PCC (source node) an answer for the requested route

Some variants of BRPC are studied. For example, in [26] authors can describe k-BRPC. As mentioned before BRPC mechanism uses a simple-node topology abstraction to establish shortest domain sequence. The main idea is that instead of providing a single sequence of domains, you can get several different sequences (in this case domain-disjoint). As we get different path end-to-end, in the case of a sequence of domains cannot be established, we will have another backup sequence and de blocking probability can be reduced. On the other hand, this mechanism collects more routing information and in consequence sometimes the first shortest path can be more optimal than the BRPC procedure. For example, in Figure 3.5 the maximum value of k is two because in this network is impossible get more than two domain-disjoint end-to-end routes. They concluded that k-BRPC drastically reduces blocking probability in comparison to standard BRPC.

3.2.2.2. Hierarchical Path Computation Element (H-PCE)

The IETF has also introduced the concept of the Hierarchical PCE (H-PCE) architecture [12], showing how to coordinate several PCEs in order to collect information from the whole set of domains in a network and then derives an optimal end-to-end path without assuming a predetermined domain sequence.

The main idea of hierarchy is defined to control and manage a group of network entities called child PCEs interconnected to a higher hierarchically level PCE, called the Parent PCE. Specifically, this architecture defines the interfaces, functionalities and the end-to-end path procedures at each hierarchical level using client-server architecture.

This hierarchical coordination is based on the PCEP. This mechanism provides low connection blocking probability at expenses of a huge amount of control overhead messages. However, in H-PCE, for each end-to-end LSP computation, updated route information to the complete set of domains is requested.

The selection of the domain sequence is essential to determine the optimal end-to-end path in multi-domain networks. In H-PCE, a Parent PCE maintains a domain topology map that contains the child domains and their interconnections. Each domain has at least one PCE (child PCE) capable of computing paths across the domain, and at the same time, it is managed by the Parent PCE. Figure 6.1 shows the physical topology of a multi-domain network and Figure 6.3 shows the domain topology map which contains the inter-domain links and the border nodes from each domain. In such architecture, the Parent PCE knows the identity and location of the child PCEs responsible for the child domains.

To maintain domain confidentiality, the Parent PCE only is aware of the topology and connections between domains. On the other hand, each child PCE does not know the topology of the other domains.

Figure below shows an example of how a network is structured, controlled by H-PCE. In this case PCE 5 is the Parent PCE.

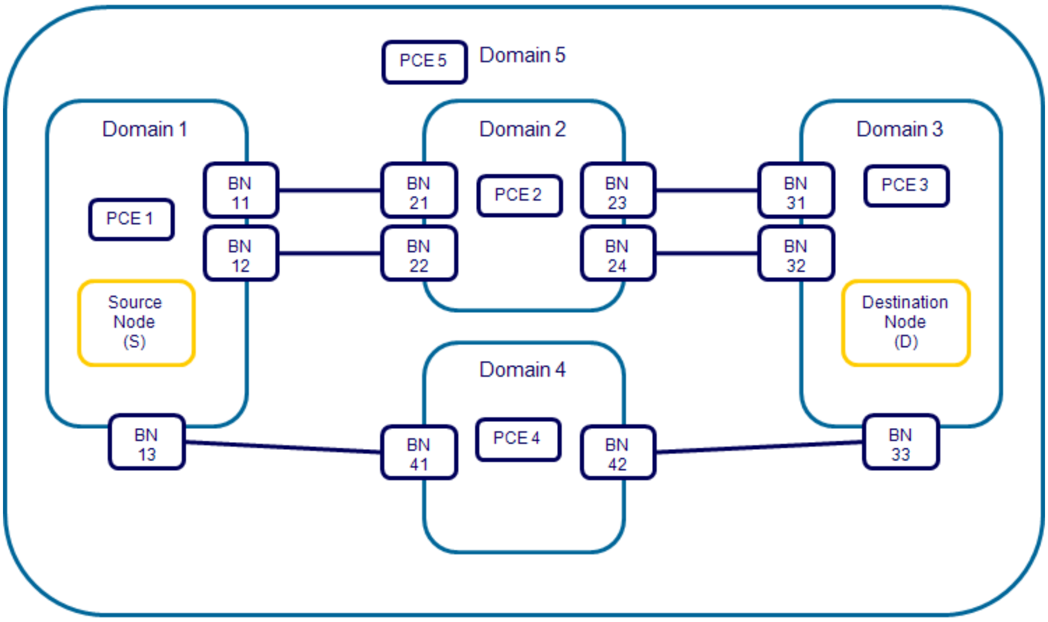

Figure 3.8 H-PCE network example [16]

An example of the connection establishment process is:

- The source PCC sends a request to the PCE responsible for its domain (PCE1) for a path to the destination node.
- PCE 1 determines the destination, is not in domain.
- PCE 1 sends a computation request to its parent PCE (PCE 5).
- The parent PCE determines that the destination is in Domain 3.
- Parent PCE determines the likely domain paths according to the domain interconnectivity and TE capabilities between the domains. For example, three domain paths are determined.
- PCE 5 sends edge-to-edge path computation requests to PCE 2 which is responsible for Domain 2.
- PCE 5 sends source-to-edge path computation requests to PCE 1 which is responsible for Domain 1.

- PCE 5 sends edge-to-destination path computation requests to PCE3 which is responsible for Domain 3.

- PCE 5 correlates all the computation responses from each child PCE, adds in the information about the inter-domain links, and applies any requested and locally configured policies.

- PCE 5 then selects the optimal end-to-end multi-domain path that meets the policies and objective functions, and supplies the resulting path to PCE 1.

4. PCE SOURCE ROUTING COMPUTATION

This chapter explains the way to establish a path without PCE's cooperation. It also explains the proposals for improve this method.

4.1. Computational method

The main idea is that the source node can establish a sequence of domains without requesting other PCE's. With this idea, is essential have a global network abstraction and update regularly the availability of network resources. Each PCE has complete information on the resources of his domain and part of other domains (topology abstraction).

So if the TED is recent enough, the PCE source can calculate the route without the need for communication between other PCEs, such as BRPC or H-PCE. Therefore, the PCE provides an optimal route to the destination domain. Using this method, sometimes we not choose the best end-to-end route. This is because if the destination node is a border node will have knowledge of their position in the global network and thus get a optimal end-to-end path. But if the node is not a border node, known only to the domain belongs. In some of these occasions the entry border node to the destination domain is not the path that provides shortest end-to-end route, thus, this implies a sub-optimal end-to-end path. After selecting the path end-to-end using RSVP-TE protocol for establishing connection.

4.1.1. Topology abstraction selection

Overall full-mesh abstraction provides more accurate intra-domain usage state, albeit at the cost of significant computational complexities at the border nodes and higher inter-domain routing loads. This chapter is focused on the full-mesh abstraction scheme, since it provides better performance than the other abstraction schemes.

4.2. Proposed mechanisms

In this section, we propose two different mechanisms to enhance the domain virtual topology update and its dissemination across different domains. Intra-domain nodes are considered to be all-optical whereas border nodes perform full opto-electronic conversion. Each domain maintains at least one dedicated PCE to build a complete graph of virtual links between all its border nodes (i.e., a full-mesh abstraction). It is assumed that the PCEs have full resource visibility of their domains as provided by OSPF-TE link-state routing protocol.

Then, each PCE disseminates the abstracted topology of the domain to the remainder PCEs. This way, every PCE has a global graph of the multi-domain network, which will be used for the computation of inter-domain path upon an end-to-end connection provisioning request. Specifically, every connection request between two nodes is routed according to source-routing loose path selection based on the minimum cost path. The source PCE (which has a full view of its own domain and the aggregated graph from the rest of the network) calculates the complete path inside its domain and the domain sequence to reach the destination node. After that, PCEs from all the transit domains in the sequence select the proper shortest intra-domain route between their border nodes. At this point, the inter-domain end-to-end source-destination path is determined.

Nevertheless, as the number of allocated connections (both intra and inter-domain) increases, the cost of the virtual link of the corresponding full-mesh abstractions must be updated. Then, the updated topology abstraction must be disseminated. However, such dissemination must be performed in a controlled manner, in order to keep limited the network overhead and increase multi-domain routing scalability.

To address these problems, we introduce two different policies, each one based on different update criteria and different aggregated information to be shared among domains.

4.2.1. Allocated path (AP)

The virtual topology is updated when an established connection (both intra and inter-domain) modifies the cost of some virtual links. The update message is based on a set of virtual links whose costs have been changed since the previous triggered update.

4.2.2. Inter-Domain Transit Path

Inter-Domain Transit Path (IDTP) is a triggering policy designed to maximize the efficiency of the distributed updates among PCEs. When a connection is allocated in a domain, the domain network resources are occupied and its full-mesh abstraction is modified. In the transit domains, if a huge number of inter-domain connections are allocated, the virtual link costs drastically change, driving to an outdated multi-domain network graph. Whether the number of established connections in a transit domain (M) exceeds a pre-defined threshold (N), the PCE of the corresponding domain disseminates the updated topology abstraction to all neighbouring PCEs.

The updated topology abstraction consists of those virtual links whose costs have been changed with respect to the previous triggered update. The shortest path cost between border nodes is assigned according to the link administrative weights.

4.2.3. Inter-Domain Transit Path – Common Cost Balancing (IDTP-CCB)

In this policy, all virtual links in a certain domain have a unique common cost (CC). As the previous mechanism, the dissemination of the updated abstraction topology is triggered once the number of allocated connections, M, exceeds the threshold N. For each domain, the PCE computes the whole set of virtual links cost and assigns the same CC to all of them. This single cost value is then disseminated to all the remainder PCEs. This is to provide a lower amount of control overhead, and at the same time, allows avoiding confidentiality issue among domains (operators).

The disseminated CC is calculated (according to (4.3)) as the average cost (AC) between the set of virtual links in a domain (T) divided by the nodal degree (ND) of that domain.

$$ND = \frac{\text{Number of Links}}{\text{Number of Nodes}} \tag{4.1}$$

$$AC = \frac{\sum_{i=1}^{T} (\text{Virtual Link Cost})_i}{\text{Number of Virtual Links}} \tag{4.2}$$

$$CC = \frac{AC}{ND} \tag{4.3}$$

The (Virtual Link is also calculated assuming the shortest path cost between border nodes in accordance with the resource occupancy in that specific domain. CC is different in each domain due to the physical intra-domain topology; therefore a dynamic network load balancing distribution of the number of allocated transit connections, in comparison to the physical available resources, is created.

The following table shows the results when applying these formulas to Figure 6.1. Taking into account that the cost of one virtual link is equal to the number of hopes of the shortest path between border nodes

Table 4.1 Nodal degree, average cost and common cost values of 9-domain topology

Domain	ND	AC	CC
1	2,75	7,29	2,65
2	2,29	8,75	3,82
3	2,86	7,00	2,45
4	2	10,01	5,01
5	2,75	7,29	2,65
6	2,4	8,35	3,48
7	2,33	8,59	3,68
8	2,57	7,83	3,04
9	2,29	8,75	3,82

Two scenarios have been considered as feasible candidates to deploy the aforementioned mechanisms, namely, OSPF-TE areas based. In the former a new summary opaque LSA with inter-area scope would be needed to disseminate the virtual topology information. In the latter, the already defined type 11 opaque LSAs which have AS external scope [10] could be used to deal with the virtual topology dissemination. Figure 4.5 shows the disseminated message and the proposed extension for the new field.

```
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|            LS age             |    Options    |       11      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Opaque Type  |               Opaque ID                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      Advertising Router                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      LS sequence number                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         LS checksum           |             length            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+-                        Common cost                         -+
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 4.5 Opaque LSA message

4.2.4. Static Balancing (SB)

The SB policy is based on the computation of a unique cost CC for the whole set of virtual link costs in the domain full-mesh abstraction. More specifically, the same cost for the virtual links, as the one in IDTP-CCB is computed and then disseminated during the network boot-up phase; as a consequence, such costs are statically configured and the updated cost values are not disseminated during the network operation.

4.2.5. Game theory based mechanisms

Some domains are more often than other transit domains, this translates into an increase in these domains blocking probability on the less used as transit. To balance this charge, these mechanisms are developed.
Basic criteria of these methods are: In normal state, each domain cooperates with the others disseminating its common cost (computed according to IDTP-CCB). If a domain is overloaded, it disseminates a CC higher than the true value

4.2.5.1. Blocking probability (BP) threshold (BPT)

The basic idea of this triggering policy is that the PCE updates the information when domain BP is equal or higher than a determined threshold (e.g., 1%).
This policy triggers an update when domain BP returns down the threshold, with the true CC.

4.2.5.2. Blocked path counter (BPC)

Each PCE manages an internal counter of blocked connections. If number of consecutive blocked connections is equal to *K* (e.g., K = 3) a higher CC is disseminated. Then, if number of consecutive accepted connections is equal to *K*, the true CC is disseminated.

5. HYBRID PATH COMPUTATION (HPC)

This chapter explains the proposals hybrid mechanism to find a tradeoff between BRPC and H-PCE.

5.1. Proposed mechanism

H-PCE mechanism has better resource utilization than BRPC mechanism. On the other hand H-PCE requires much higher number of messages that BRPC to collect information to compute end-to-end inter-domain LSP. So depending on the loads H-PCE introduces an unnecessary amount of overhead. HPC was born from the idea of regulating between BRPC and HPC in function of the offered load.

The structure used by the HPC mechanism is the same as that used in H-PCE. Where every domain has a child PCE and one parent PCE for the global network.

BRPC uses a pre-determined sequence of domains to establish an end-to-end inter-domain path. This sequence is statically provided by the Border Gateway Protocol (BGP) [15]. If the destination domain is adjacent to source domain, BRPC resources utilization has almost the same as H-PCE. On the other hand the larger the number of domains that have to traversing end-to-end inter-domain path, the difference between BRPC and H-PCE increases. Thereby set the parameter k. This parameter controls at what point mechanism is used BRPC or H-PCE. The value of these parameters depends on the number of domains in an end-to-end path. As can be seen in Figure 6.1 the path end-to-end is longer that contains five domains. So for this network can only use a k ranging from one to five.

Nonetheless, once a child PCE is not able to provide a proper end-to-end inter-domain path using BRPC or the number of domains to be crossed surpasses a pre-defined threshold k, the child PCE delegates to the Parent PCE the path computation, and the standard H-PCE procedure is thus applied. If k value is equal to one always the connections are established using H-PCE, because the restriction of a single domain forces that all inter-domain connections are computed by H-PCE. Table 5.1 shows the mechanism used depending on the k value.

Table 5.1 Use mechanism

K value	Mechanism
1	H-PCE
2	H-PCE and BRPC
3	H-PCE and BRPC
4	H-PCE and BRPC
5	BRPC

HPC supposes that a shortest domain path in the topology is more probable to be the optimal one to allocate the requested end-to-end path. As the number of domain hops increases, it becomes more difficult to select the most appropriate sequence to allocate an end-to-end path and for this reason it is more suitable use H-PCE instead BRPC.

HPC improves the use of PCE child with the ability to choose the calculation method between H BRPC and PCE. Depending on the number of domains previously established, the child PCE runs each mechanism that the parent PCE considers it necessary. The parent PCE will have a partial knowledge of the global network resources used and depending on the offered load it decides k value. These changes are notified in each domain TED.

6. SIMULATION SCENARIO

These mechanisms have been tested on by running OMNeT++ simulations. Specifically, detailed node and process models are coded in C/C++ to implement all of the proposed inter-domain routing, signalling, and path computation algorithms.

A 9-domain transport network composed by 61 nodes and 95 links which 19 are inter-domain links is used to obtain results of the mechanisms described above. Carrying each one 8 wavelengths per link. The global network abstraction is composed by 78 links and each PCE manages in average 8.6 virtual links.

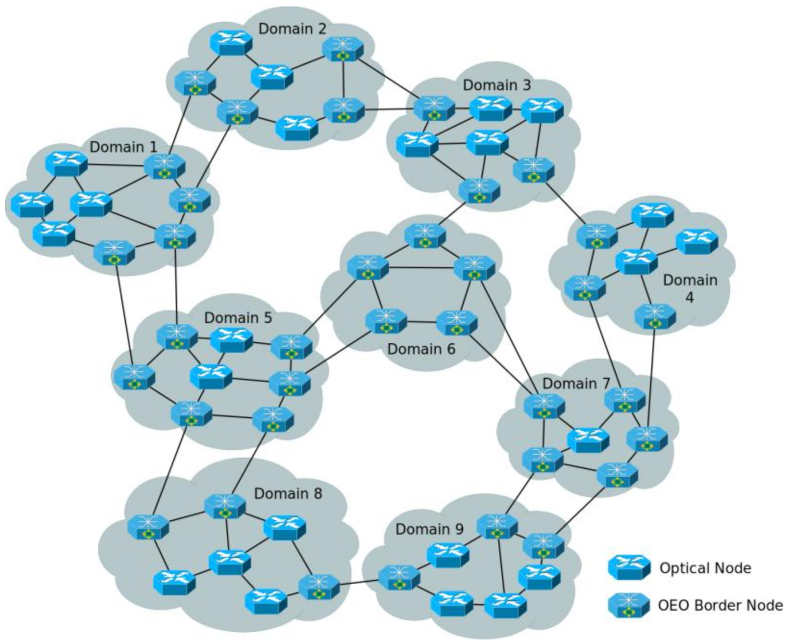

Figure 6.1 9-domain topology

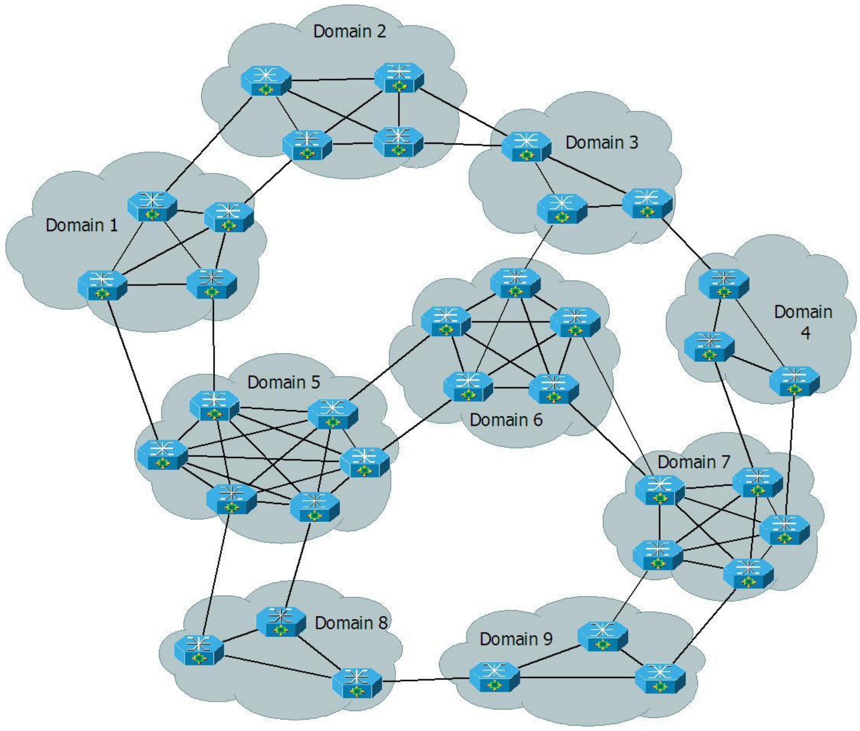

Figure 6.2 9-domain topology full-mesh abstraction

In total 10^5 Poisson bidirectional connection requests are generated following 70/30% intra/inter-domain ratio. For inter-domain connections, source and destination domains are uniformly selected and source/destination nodes are uniformly chosen in their respective domains. Source and destination nodes are randomly selected for intra-domain connections. All generated requests demand a whole wavelength capacity and mean holding time (HT) is set to 600 seconds following an exponential distribution. Request inter-arrival time is also exponentially distributed and varies with the network offered load.

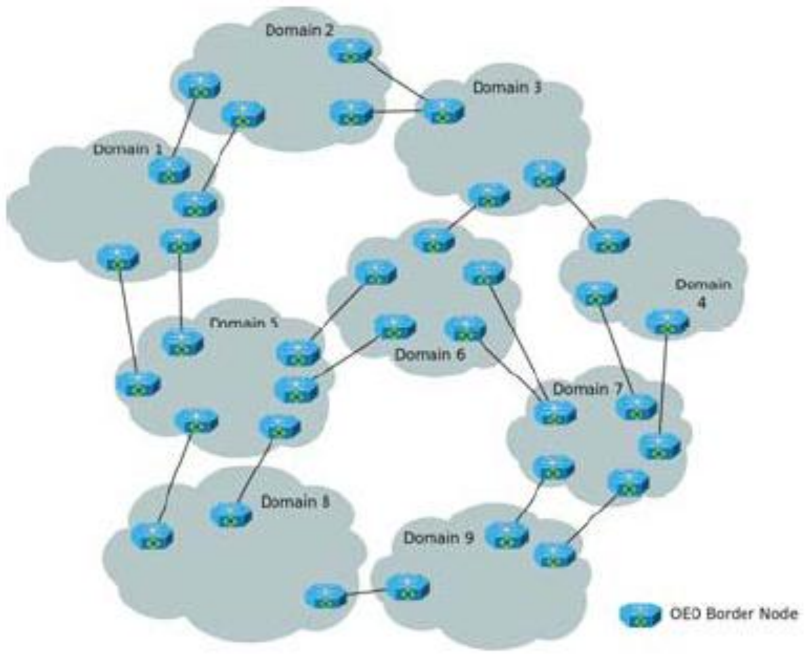

Figure 6.3 Domain map managed by the Parent PCE used to calculate the domain sequences

7. RESULTS

This chapter discusses the results obtained by applying the conditions described in chapter 6 on the solutions proposed in chapters 4 and 5.

7.1. Source routing computation

Figure 7.1 shows the network connection blocking probability improvement compared to per-domain mechanism

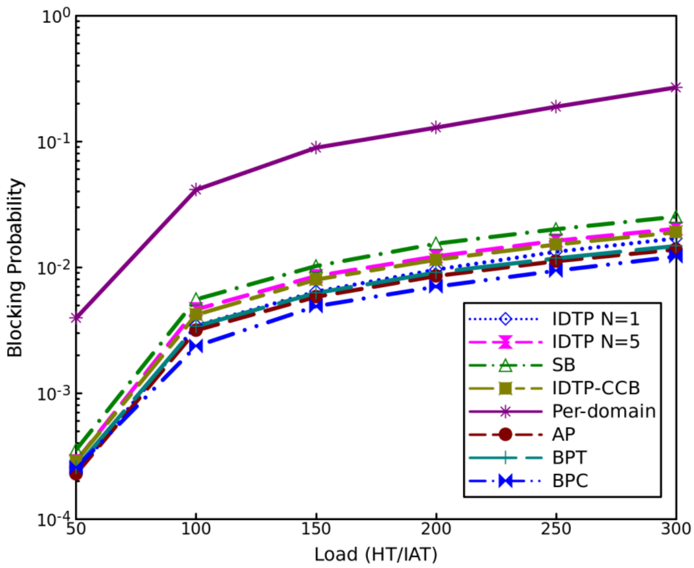

Figure 7.1 Blocking probability

Figure 7.2 reflects the average number of virtual links cost fields performed by IDTP-CCB (using only one cost field for each virtual link) and IDTP N=1, 5, 10, 20 (using as much as virtual link cost fields has each domain full-mesh abstraction). This has been quantified to serve the same set of offered intra- and inter-domain connections under a fixed offered load of 200 Erlang (Bp ≈ 1%). As expected, for the IDTP with N=1 policy, an increment of about 5% in terms of the present fields in its distributed opaque LSAs is experimented in front of IDTP-CCB policy, that only sends a cost field including the same CC for the whole set of virtual links.

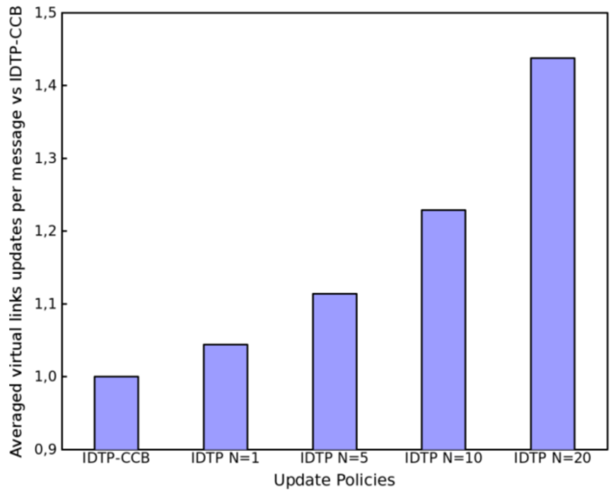

Figure 7.2 Average links update per message

Assuming an increment of the parameter N, IDTP based solutions require on average a higher number of fields (virtual link costs) in their opaque LSAs while IDTP-CCB presents a flat performance maintaining just one field (since the disseminate cost is unique) in each opaque LSA. As seen in Figure 7.2, for IDTP with N=5, the size of the virtual link cost fields is about 15% higher that the IDTP-CCB policy.

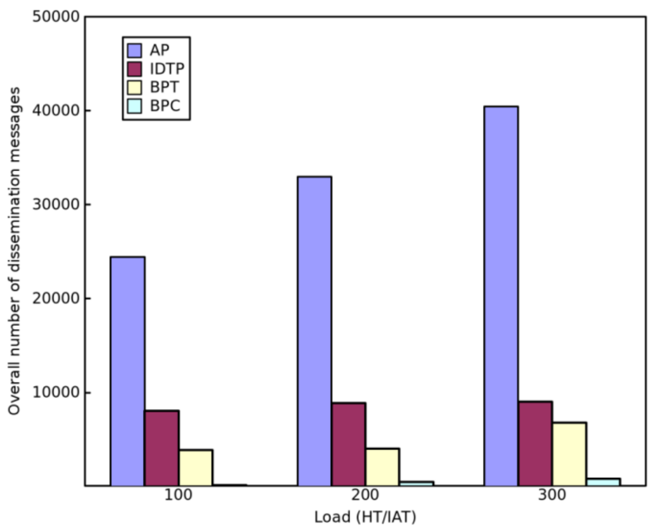

Figure 7.3 Overall network overhead

As shown in Figure 7.3, traffic balancing policies significantly reduce the overhead. Especially BPC remains practically negligible compared to the rest. IDTP police grows slowly, but as you can see BTP grows very fast for heavy loads.

Figure 7.4 shows the Average number of hops of end-to-end connections. As expected, balancing policies on average get a number of link hops higher than other policies. This is basically when part of the network is heavily loaded these policies do give more back from the necessary path failing to establish the link by the shortest route.

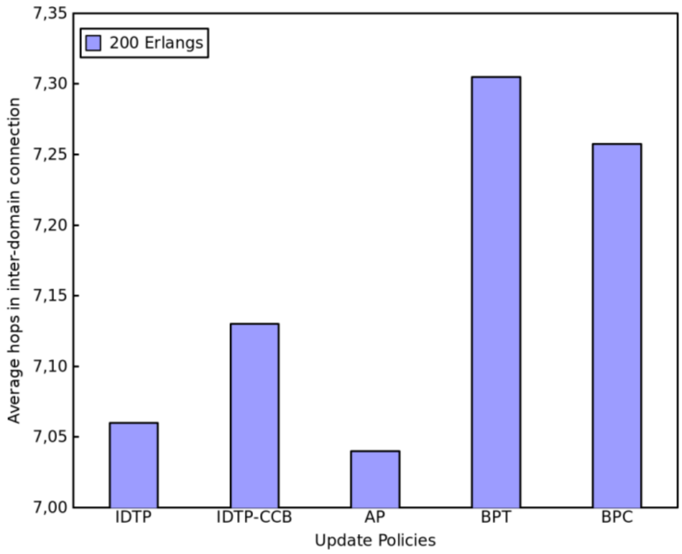

Figure 7.4 Average number of hops of end-to-end connections

7.2. Hybrid path computation

Figure 7.5 shows the overall network connection Bp (blocking probability) achieved by H-PCE, HPC (with k = 2, 3) and BRPC respectively, as a function of offered load.

Using HPC procedure with k = 2, BRPC is applied only when the destination node is on adjacent domain while the HPC procedure with k = 3 uses BRPC if the domains sequence includes one or two transit domains.

BRPC have the worst Bp because only collects routing information a pre-configured domain sequence meanwhile HPCE presents the best Bp because it computes the path using all the collected routing information from the child

PCEs. For low offered loads, HPC generates similar Bp in comparison to H-PCE. HPC uses the enhanced child PCE capacity to switch between BRPC and H-PCE, providing a not significant increase of the Bp for higher offered loads. In particular, for 200 Erlang, HPC with k = 2 performs a Bp around 1%, being slightly higher than H-PCE.

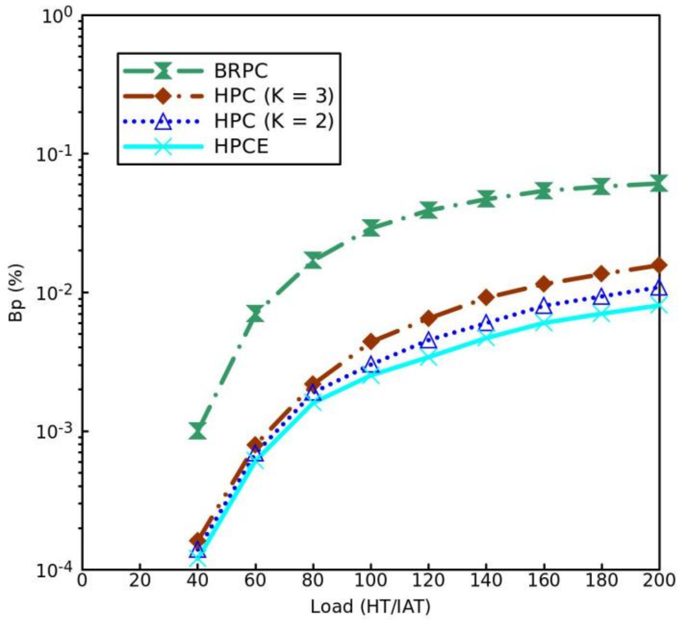

Figure 7.5 Connection blocking probability in a BRPC, HPC and HPCE

Figure 7.5 also depicts that in some cases, executing BRPC using the domain sequence provided by the Parent PCE is enough to perfectly allocate an inter-domain path. For the least loaded network scenarios, it seems the most suitable path computation method because the generated network overhead is lower and the performed Bp is acceptable.

Table 7.1 analyzes the overhead reduction deploying the hybrid approach. The HPC procedure with k = 2 generates a reduction of the network control overhead around 72 %. Moreover, HPC with k = 3 improves around the 75 % the Bp performance in comparison to BRPC only increasing by the 20 % the network control overhead messages. Table 7.2 depicts the utilization of the Parent PCE by applying the HPC.

Table 7.1 Relative overhead reduction in comparison to H-PCE (%)

HPC (k=2)	72
HPC (k=3)	39
BRPC	20

Table 7.2 Parent PCE utilization (%)

HPC (k=2)	76
HPC (k=3)	31

Specifically, running the HPC procedure with k = 3 about one third of the inter-domain path computations requires the utilization of the Parent PCE. If HPC with k = 2 is run, the Parent PCE does not intervene in about one fourth of the path computations. Therefore, proposed method reduces the Parent PCE computational load increasing the cooperation between the child PCEs.

CONCLUSIONS

A wide range of networking technologies is being deployed across different long-haul and metro/regional networking domains. As a consequence of the need of a higher bandwidth, these technologies trend to converge to the Next Generation Network (NGN). NGN are characterized for being composed by two layers, one is the physical (DWDM) and the other is for the management (IP / GMPLS).

The main inconvenience of the optical networks spanning different domains is the inter-domain path establishment owing to the resources availability of the other domains. In order to solve this drawback, IETF has defined some protocols for the multi-domain routing and signaling. In addition to these protocols, this entity has also introduced some mechanism for the inter-domain path establishment (Per-domain path computation, BRPC and H-PCE).

This master thesis presents a comprehensive framework for path provisioning in multi-domain networks, which improve the mechanisms established by the IETF. This proposed framework can be sorted in two types, the cooperation between PCE and without cooperation.

Regarding the non cooperation procedure, source routing path computation compare different updated domain topological information triggering policies, which improve the routing scalability in multi-domain optical networks. To compute optimal end-to-end paths crossing different domains, the exchange of some aggregated topological information of each domain is required, at expenses to increase the network control overhead among the PCEs. The policies discussed in this paper allow reducing the control messages exchanges while keeping the confidentiality requirements among the domain. On the basis of the simulation results, IDTP-CCB is presented as the best solution to reach a trade-off between network overhead (and thus routing scalability) and global connection blocking probability. At the same time, it allows to face in an efficient way the confidentiality concerns among domain operators. Future efforts will be devoted to design more advanced triggering update policies, able to provide even better solutions in terms of blocking probability and routing scalability. The extensions to current standard GMPLS protocols required to disseminate the information to be shared will be also defined.

On the other hand, the proposed HPC procedure is based on the pre-established length of the domain sequence. To calculate optimal routes in a network of multiple domains, sharing part of the information of domains is necessary, but this leads to an increase in overhead. HPC drastically reduce the overhead in comparison to H-PCE that is the best solution provided by the IETF maintaining a similar blocking probability. Simulation results shows that this proposed procedure is the best solution to reach a trade-off between network control overhead and connection blocking probability. In addition, it maintains the confidentiality among independent domains.

Therefore, some conclusions obtained from this thesis is the improvement of the computational mechanisms proposed by IETF when a path is computed only on the source PCE and when PCEs cooperate to compute the path. In addition to this conclusion, this thesis has deduced that the HPC introduce more overhead in the network than the source routing computation mechanism, but its blocking probability is slightly reduced.

Considering that the physical equipments are renovated by disuse or irreversible failure, the main objective of this master thesis is to optimize physical resources. It entails a reduction of electronic waste that nowadays is a concern for their impact on the environment.

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