**Ph.D. Dissertation in Engineering**

# A mediator for Resolving the Network Management Issues Between the IP Layer and the Transport Layer

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## Abstract

There is a wide consensus among telecom vendors and telecom operators, that next decade will be evidence of bandwidth incentive applications that need an intelligent and flexible Internet architecture. The Internet Protocol (IP) over the optical network solutions expected to reduce capital expenditure and the operational expenditure, while improving overall network performance. Central to this promise is an autonomic network management system is essential to address the future applications demands and to allow new services to be run over the network.

Unfortunately, practice lags far behind this promise. The current schism between the IP part and the transport part of telecommunication companies isolated the two Network Management Systems (NMSs). Thus, even a basic operation, such as service provisioning, require long time and multiple human intervention. As a result, carriers are seeking ways to reduce the dependency on manual processes.

In a environment where the IP network, and the transport network management systems are isolated, even simple operations, such as provisioning a VPN, require human-assisted configurations which is error prone, and time consuming. As a result, carriers are in quest of ways to alleviate the dependence on manual processes.

With the intention of addressing the problem, IETF and the ITU introduced two well-known standardized control plane frameworks. While the ASON/GMPLS control plane framework, standardized by ITU-T and IETF, theoretically address the network management issues, the coordination of management task between the two layers remains unsolved. Furthermore, practice shows that the solutions proposed by the standardization organizations are not desirable to the network operators.

In this dissertation, we introduce a cost model to estimate the new technology deployment cost and its efficiency in networks which is up and running. In addition we propose architecture for a mediator model between the IP/MPLS and the transport layers to facilitate the coordination and automation of management tasks, evaluate the mediator model’s impact on the value creation chain of the Internet ecosystem, and propose an algorithm to demonstrate the ability of the mediator model for computing the multi-layer paths for SDH/SONET networks.

**Key words:** IP Network, Transport network, Network Management System, Integration, Coordination.

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# Chapter 1. Overall Introduction

## 1.1 Background

Present day data communication networks were traditionally designed to provide voice communication services. When the World Wide Web (WWW) was born, telecommunication networks used to transmit signals over fiber optic networks with synchronous digital hierarchy (SDH) and synchronous optical network (SONET) technologies. The SDH and SONET technologies were standardized by the International Telecommunication Union (ITU) and the American National Standards Institute (ANSI). SDH/SONET was designed to carry voice channels. The circuit switched the SDH/SONET technologies with a time division multiplexing (TDM) system, providing the best protection mechanisms as well as the required bandwidth granularities for the voice signals. The telecommunication network was selected as the connectivity provider for the newly born Internet because of its capability for transmitting low transmission rate data over SDH/SONET networks, and because of its worldwide reachability.

While in the early stages of the Internet no one could expect that soon data communication would surpass voice communication, this is a reality in today's practice. This phenomenon is observable by the still increasing expansion and penetration of the Internet and the popularity of bandwidth intensive IP-based applications such as video conferencing and IP-TV. Despite the fact that SDH/SONET technology opened a new era in voice communication advancement, the requirement for handling large amounts of IP traffic and providing fast provisioning services has now become a burden for the SDH/SONET network technology.

According to Zhang and Zhao [2008], transport service providers are suffering from manual, error prone, and long link/service provisioning. Furthermore, they suffer from low resource utilization, hard interoperability, complex network management, reliability and scalability issues.

While the Internet opened new business opportunities for telecommunication operators, the expansion of networks worldwide, switching technology and communication protocol differences isolated the IP and transport layers. Additionally, the use of multi-standard and vendor specific technology has further increased the already high operational costs.

Efforts to overcome interoperability issues between the layers and the domain in the Internet can be classified into four main groups, namely the efforts of the standardization organizations, the research support organizations, the industry, and those of individual scholars.

The major result of a decade-long effort of the standardization organizations (i.e. IETF and ITU-T) was the introduction of GMPLS and ASON control plan frameworks. The Generalized Multi-Protocol Label Switching (GMPLS) framework has been developed by the IETF. GMPLS is a centralized network control framework designed to cope with multiple-layer and multi-domain environments. It comprises hybrid network node design, support packet switching, label switching, time slot switching, wavelength switching, and fiber switching technologies.

In competition to GMPLS, ITU-T introduced architecture for an Automatically Switched Optical Network (ASON). The ITU-T approach is based on the interfaces between the layers and the domain. The User Network Interface (UNI), the Internal Network to Network Interface (I-NNI) and the External Network to Network Interface (E-INNI) are the interfaces that connect the different layers and domains with each other. The introduction of the above-mentioned interfaces opened the opportunity for automatically switching three different types of optical connection, namely soft connections, the permanent connections, and soft permanent connections.

While both the IETF and ITU-T frameworks try to address the network management issue between the IP layer and the transport layer, as well as between the different transport domains in the Internet, the approaches of each organization are different. To streamline their approaches as well as to provide a common solution to the problem, the IETF and the ITU-T combined the advantages of both frameworks and introduced the ASON/GMPLS control plan framework. The ASON/GMPLS approach is based on the ASON architecture and uses GMPLS protocols.

While the expectation of the GMPLS and ASON/GMPLS to resolve the shortcomings of the IP and transport layers was enormous, the actual network management deployment situation suggests that neither approach was found to be a desirable solution for the network operators.

Research support organizations, such as the EU, FP6 and FP7, have been funding several research projects with the aim of improving the proposed solutions of IETF and ITU-T, or to introduce a separate solution to the problem. G-Lambda, IPsphere, MUPBED, NOBEL, and OSCARS are examples of these efforts. The ONE project, which is funded by the EU FP7, is currently prototyping a mediator model called the ONE adapter. The ONE adapter model is designed to be integrated into the IP layer with the capability of serving one request at a time. While the mediator model concept was first developed by the ONE project, its integration into the IP/MPLS layer is challenging. The ONE consortium assumes a trusted relationship between the IP/MPLS and the transport layers, and allows the IP/MPLS network to access and make changes to the transport layer.

The telecommunication industry hardware and software vendors also introduced their own solutions to the problem. The Cisco CRS-1, ONS 15454, Ericsson network management product, and Nokia-Siemens solution are examples of industry efforts.

The network management functions are complex, combining fault management, configuration management, accounting management, performance management and security management. To simplify network management, the above-mentioned network management functions are classified and standardized by the Open System Interconnection (OIS). Due to the complex nature of the problem individual researchers have tried to address specific parts of the problem, such as security or routing issues.

The IP/MPLS layer (the IP/MPLS layer are networks that use IP and MPLS protocols, respectively) and the transport layer management issues are consequences of the historical dedication of each layer, as well as the technical differences possessed by each layer. To explain why the IP and transport layers cannot automatically communicate with each other, in this chapter we briefly discuss the reasons behind the low interoperability between the two layers in the following sections.

## 1.2 Communication Networks' Interoperability Factors

In general, interoperability requires a common communication language between the parties as well as the usage of a standardized technology at every layer and in the domain. In the next subsection, we briefly discuss these main requirements in more detail.

### 1.2.1 Switching Technology Differences

One of the essential factors for interoperability between the information and communication networks is the switching technology. The early stage of telephony provided evidence of point-to-point connectivity between devices. An alternative to point-to-point communication is to establish a communication network where connections between devices can be established by switching the communication lines along the path between the source and the destination nodes. While multiple types of switching system such as circuit switching, packet switching, message switching, and burst switching exists, we concentrate our focus on circuit and the packet switching technologies which is commonly being used with IP/MPLS and transport networks.

#### 1.2.1.1 Circuit Switching

Circuit switching is the first switching system introduced in information and communication systems. In circuit switched networks a dedicated physical path must be established between the source and the destination points before transmitting the information (voice signal or data signal). Therefore, the channel capacity must be reserved between the source and the destination nodes along the path. The three different phases of circuit switched communication discussed by Farahmand and Zhang [2007] are circuit establishment, data transmission and connection release. To ensure information delivery between the source and destination nodes, circuit capacity must be equal to the peak transmission rate. This means that circuit switching is a connection oriented and peak allocated communication. The above-mentioned characteristics allow circuit switching to be the best switching system in terms of delay, jitter and bandwidth guarantees. In summary, circuit switching allows the isolation of traffic between the channels as well as traffic engineering. The bandwidth inefficiency and signaling overhead can be considered as the main disadvantage of circuit switching. Currently, circuit switching techniques are being used in transport networks.

#### 1.2.1.2 Packet Switching

Packet switching can be considered as a basis for the Internet Protocol (IP). In packet switching technology, information flow fragments into packets. Then packets are sent one by one to the nearest node from where it is forwarded to the corresponding next node. This process repeats until the packet reaches its destination node. Routing decisions are independent of past decisions and are performed at every node. The store and forward mechanisms are carried out in the IP routers, allowing the data packet to be received, stored, processed and then transmitted to the next hop using the header information. In the Internet, where packet switching is considered the most important switching technology, the services are connectionless and best effort. This means that the Internet does not provide a guarantee of delivery. While reliability, flow control and connection oriented services are provided by the end-to-end mechanisms like the Transmission Control Protocol (TCP), there are no guarantees in terms of bandwidth, delay, jitter and packet drops due to the IP layer best effort services [Rosen, Viswanathan and Callon, 2001].

As can be seen, circuit switching and packet switching are the two main switching systems used in the transport and the IP layers, respectively. They are different in terms of connection orientation as well as in their technology and nature.

### 1.2.2 Communication Protocol Differences

The second major interoperability requirement between the IP and transport layers is the communication protocol. The two main communication protocols currently being used in the IP and transport layers are the Simple Network Management Protocol (SNMP) and Transaction Language 1 (TL1), respectively.

#### 1.2.2.1 Simple Network Management Protocol (SNMP)

The Simple Network Management Protocol, which was introduced in 1988, is capable of managing any kind of network device such as audio systems, video systems, HVAC systems as well as toasters [Lima and Alves, 2006]. Currently, three distinct versions of the SNMP protocol exist, namely SNMPv1, SNMPv2 and SNMPv3. Due to the popularity of the SNMP protocol, hardware producers are including support for this protocol in their products. While SNMP is the most mature protocol in the IP layer, it lacks the management capabilities required to allow automatic interaction and communication between the two layers.

Figure 1.1 shows the SNMP message sequence, which is the SNMP version, the SNMP community string and the SNMP PDU (Protocol Data Unit), such as get request and set request.

The SNMP version and the Octet String are primitive data types and only have one layer, but the SNMP PDU is made up of smaller layers, such as request ID, Error, Error index, object identifier and value.

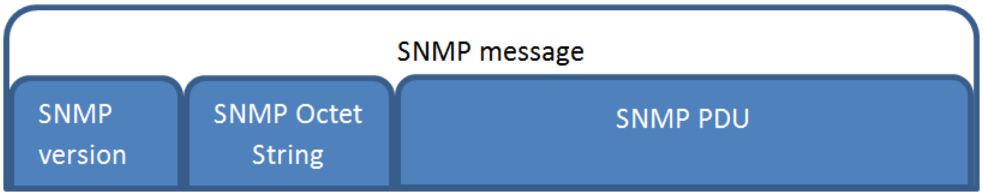



Figure1.1 SNMP message sequence diagram

#### 1.2.2.2 Transaction Language 1

TL1 is a set of American standard codes for the information interchange instruction called (ASCII) [Cisco ONS]. TL1 as a communication language in the transport layer is being used by an operation support system (OSS) to manage the network devices. To allow communication between the operating systems, network elements and personnel, TL1 provides a set of standard messages. The two main types of message that the TL1 language defines are the command/response and autonomous message. The command/response message is initiated by the user and has two parts. These are the request, which can be considered the input message and is used to issue the request. The response message is the output message from a network element to the operation support system.

Autonomous messages are used to report alarms, and configuration or condition changes that are triggered by the network element. TL1 is designed to manage the SDH/SONET network devices and can be connected once per session. TL1 can be connected via CTC, telnet or craft interfaces. TL1 messages follow a fixed structure for the TL1 input message, TL1 output message, TL1 acknowledgement message and TL1 autonomous message.

As can be seen, TL1 and the simple Network Management Protocol are totally different in terms of message structure and purpose. They are used in different layers in the Internet. To allow interoperability between the two layers one has to overcome this problem.

### 1.2.3 Multi-vendor technology usage

Apart from the above-mentioned differences, the multi-vendor technology usage in different layers and domains in the Internet also impedes the interoperability between the IP/MPLS layer and the transport layer. There are two major players in the networking equipment market, each of which has its own standard. These are Cisco and Juniper. They compete with each other and try to gain a higher market share by implementing specific functionalities to the equipment. This action increases buyers' dependency on the seller. As a matter of fact, and as stated in Seeking Alpha [2010], Cisco has a 60 percent market share for network switches and more than a 50 percent market share for routers. In contrast, Juniper has a 37 percent market share for routers and 20 percent for switches. Furthermore, in order to manage the networks, network operators are using in-house built management solutions. They also try to manage the network with many other solutions which exist in the market.

### 1.2.4 Isolated Islands

The popularity of the Internet opened business opportunities for telecommunications providers, allowing further expansion of the networks. Moreover, technological advancements motivate the network operators to invest worldwide. And thus networks become enormous and the centralized network management becomes the bottleneck. The decentralization of networks, working under the same administrative domain, increases the duplication of management functions. Consequently it increases the complexity of the network management and the operating cost of the networks.

The differences in the switching system, communication language, as well as the multi-vendor technology usage and worldwide expansion of networks, are the main reasons behind the creation of isolated islands between the networks, working under the same administrative boundary. This isolation not only makes the network management and network control harder, but also increases the network's operational cost. The fact that data and voice communication prices are dramatically reducing, aids network operators in the quest to reduce the network's operational cost and allows new services over the network to generate revenue from the capital intensive telecommunication infrastructure.

## 1.3 Problem Description and Research Motivation

Today’s Internet consists of multiple layer networks, each of which is designed for a specific purpose. They are different in terms of switching technologies and communication protocols. While the objectives of each layer are different, the final goal is to aggregate the end user’s tiny data packet into the multi gigabit fiber optic cable. The access network layer, the IP layer, the Asynchronous Transmission Mode (ATM) layer, the Synchronous Optical Network (SONET) or Synchronous Digital Hierarchy (SDH) layer and Wavelength Division Multiplexing (WDM) or Dense Division Multiplexing (DWDM) are the layers that currently exist in the Internet. The objective of this dissertation is to address the management issues of the IP and carrier layers, namely the IP and SDH/SONET layers. Due to the SDH/SONET manual network management system as well as the interoperability issues between the IP and carrier layers, today’s multilayer Internet suffers from manual- and error-prone long provisioning time, hard interoperability, complex network management, and reliability and scalability problems.

Despite the long and strong efforts of standardization bodies, the two frameworks which in the end were streamlined into a common framework (the ASON/GMPLS) were found not to be a desirable solution to the problem. According to [Narayanaswamy, 2011], Vice President of Network Architecture for Reliance Globalcom, “On paper, GMPLS does what a carrier would want, but it hasn’t worked that way in practice nor in lab tests”.

The above-mentioned challenges of standardized organization solutions and the network operator’s quest for a cost efficient, easy to deploy and non-disruptive solution to the problem, motivate us to address the problem differently to existing approaches.

## 1.4 Research Questions

In line with the objective of study and the problem mentioned above, the following questions are presented and solved as followed:

- *Why is a decade long and extensive effort of standardization organizations to address the management issues of IP and transport layers which led to the introduction of control plan frameworks found to be a non-desirable solution to the problem? See Chapter 3.*

*To answer this question, we will calculate the deployment cost of the GMPLS control plan framework and check the controversial claim of previous researchers who declare "GMPLS deployment may lead to a 50 percent reduction in the operational cost of carrier providers".*

- *How to address the IP and transport layers' management function coordination requirement in a cost effective way?*

*To address this question we will look at the current practices of IP and transport network relationship, as well as the requirements of a MM model to allow the coordination of a network management function between the two layers. To overcome the challenges we introduce a multi-input, multi-output MM architecture that needs to be deployed at the transport layer.*

- *What kinds of impact may the mediator model have in the current business model of IP/MPLS and the transport networks?*

*In answering this question we will look at the current business model of telecommunication networks, and will define the actors, their roles and relationships. We will compare the new value creation chain with the current situation to define the mediator model's impact at each layer.*

- *How to address the inefficiency of transport networks in terms of paths computation which leads to the high operational cost and long provisioning time?*

*In response to this question we will propose a path computation algorithm to address the SDH/SONET multiplexing structure, the inefficiency of the current approaches for finding a pair of disjoint paths, and consider the user preferences and the network operator's priorities and policies.*

## 1.5 Research Contribution

One of the main contributions of this dissertation is to introduce the concept of a multi-input, multi-output mediator model between the “m” number of IP and their corresponding “n” number of transport providers, which should be considered as the extension of the ONE adapter concept introduced by the ONE project.

In addition, we will define the techno-economic challenges of control plan frameworks and will specify the mediator model’s impact on the value creation activities of the Internet ecosystem. The final and major contribution of this dissertation is the introduction of an algorithm for computing the paths in SDH/SONET networks considering the multiplexing structure of SDH/SONET technology, the challenges of current approaches for finding a pair of disjoint paths, and the user and provider preferences.

## 1.6 Outline of Dissertation

This dissertation is organized into seven chapters. Chapter 1 presents the overall introduction, including the background information. Chapter 2 describes the efforts of other scholars to address the problems of network management and network control. Chapter 3 evaluates the techno-economic challenges of the control plan framework proposed. Chapter 4 introduces the multi-input, multi-output mediator model architecture and the ways we propose to address the management issues of the IP and transport layers. Chapter 5 presents the expected impacts of the mediator model on the current Internet ecosystem value creation activities. This chapter also provides information about the potential business models enabled by the introduction of the mediator model. Chapter 6 demonstrates a user preference-based path computation algorithm and its performance control, which is based on the simulation of three real networks. Chapter 7 concludes the dissertation with an overall summary and policy implications.

# Chapter 2. Literature Review

## 2.1 Network Management Functions

Network management functions have been classified by OSI into five well-known functions, namely Security management, Performance management, Accounting management, Configuration management and Fault management (FCAPS) [Network Management Model, 2004]. As the network management functions are complex, scholars have tried to study each class separately. While multiple studies can be found which address individual functions, research support organizations and industry have always addressed the problem as a complex and interrelated issue.

Considering our objectives (coordination and automation of management tasks between the IP and transport layers), in this chapter we review the literature which address the problem as a complex and interrelated issue. More specifically, we discuss the network management solutions proposed by the standardization organizations and research support organizations, as well as the solution proposed by the industry.

## 2.2 Standardization Organizations' Solution to Network Management Issues

In the current environment, where data communication has surpassed voice communication and bandwidth incentive applications such as IP-TV and P2P have become part of our daily lives, network providers are flooded with bandwidth requirements.

SDH/SONET networks as a main provider of the capacity and connectivity for the upper layer, namely the IP layer, suffers from high operational costs due to its static nature.

Meanwhile, providing differentiated services to customers has been found to be one of the main sources of revenue for carrier providers [Fawaz, 2004]. The increasing demand for bandwidth and the business opportunities for providing network services within the minimum possible time suggest that there is a need for an automatic means of path computation. Traditionally, to provision a network service, service providers log into the network management system (NMS) and manually carry out provisioning related activities. This process is time-consuming, error prone and costly. As stated by Chahine, Kirstadter and Pasqualine [2004], traditional service delivery passes through sales, administration, project management and network operation center sections, where multiple sub-department employees are involved in the process. Furthermore, due to the hard inoperability between IP and transport layers the coordination of management tasks is not possible within current practices. While in most cases both the IP and transport layers are working under the same administrative boundary the network managements are duplicated at each layer, which increases the overall service costs.

To address the demand for a flexible, intelligent and interoperable network management system, the standardization organizations have put in long and intense efforts. The results of those efforts are two main standards, namely the IETF Generalized Multi-Protocol Label Switching (GMPLS) and the ITU-T Automatically Switched Optical Network (ASON) frameworks. In the next sub-section, we will discuss those two standards, which had a big impact on the industry as well as the research community.

### 2.2.1 Internet Engineering Task Force (IETF), GMPLS Standard

The Generalized Multi-Protocol Label Switching (GMPLS) framework [Rosen, Viswanathan and Callon, 2001] is an Internet Engineering Task Force (IETF) standard. GMPLS has its root in the well-known Multi-Protocol Label Switching (MPLS) framework [Rick, 2002]. The introduction of MPLS offered great advantages to the network. Those are; the opportunity for provisioning a Virtual Private Network (VPN) to connect many diverse locations with a bandwidth much higher than the frame relay could provide, the opportunity to reduce the network operational cost and improve network security. Furthermore, to ensure the bandwidth, latency, jitter, and packet loss, MPLS provides class of service. However, these advantages are limited to MPLS networks.

GMPLS was designed to address the shortcomings of network management functions in a multi-layer multi-domain environment. This framework allows configuring of any kind of network element both automatically and dynamically through a centralized network management system focusing on interoperability. Unlike MPLS, GMPLS is capable of interoperating with different switching technologies, such as Packet Switching, Label Switching, Time Division Multiplexing, Lambda Switching and Fiber Switching technologies.

The extension of well-known protocols such as Resource Reservation Protocol with Traffic Engineering capability (RSVP-TE), Open Shortest Path First with Traffic Engineering capability (OSPF-TE) and the introduction of Link Management Protocols (LMP) make the GMPLS capable of end-to-end protection and control, automatic provisioning and multi-layer traffic engineering [Ayangar, 2006; Berger, 2003; Lang, 2005].

GMPLS is a control plan which offers dynamic end–to-end service provisioning. In GMPLS, to provision a service the operators need to define the quality of service (QoS) parameters and send them to the access node. The network control plan then defines the optical path along the network and signals the destination node to establish the connection. It allows the establishment of a connection within seconds instead of hours. In the GGMPS, the ease of service provisioning allows another important service, which is on-demand provisioning. As stated by Palmieri and Federico [2008], the GMPLS control plan framework allows the client devices to call for the connection in real time. Additionally, GMPLS guarantees traffic grooming at the age node when operating on a two layer model, namely the WDM layer and the SDH or SONET layers.

IETF introduced three different models for its control plane framework to transport the IP packets over the optical networks, namely the Peer model, the overlay model and the augmented model [Rajagopalan, 2004]. In the Peer model, the IP layer act as a peer of the transport layer. This means that a single control plan instance is required to control both layers.

In the Overlay model, the IP and transport layers separately manage routing, topology distribution and signaling in their domain. In this case two separate control planes need to be deployed in each layer, which will interact with each other via a User Network Interface (UNI).

The Augmented model is a combination of the peer and overlay models, where certain types of information forming one routing area can pass to the other. This model allows administrative domain separation between the IP and transport layers, while the routing information can be exchanged between the domains. Figure 2.1 shows the GMPLS label switched path hierarchy. As can be seen from the figure below, a GMPLS capable network can switch fibers (F), wavelengths (λ), time slots (t) and packets. In our example case a packet for time slot number 1 belonging to the wavelength number two and fiber number one is switched by the GMPLS network to the packet belonging to the time slot number 2 of the third wavelength of fiber number 2.

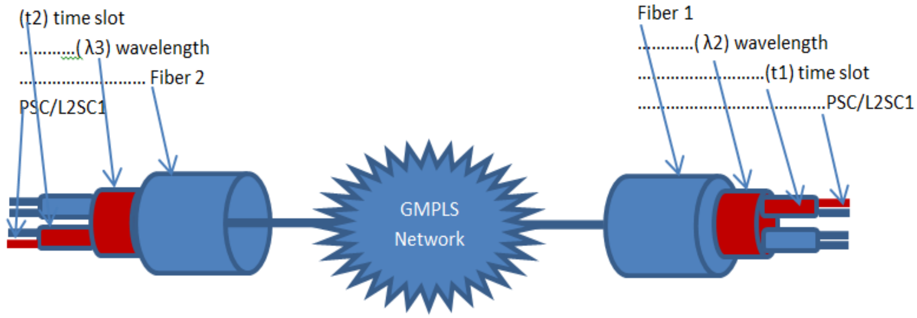



Figure 2.1 GMPLS label switched path hierarchy

Therefore, theoretically the GMPLS framework is capable of addressing the shortcomings of manual provisioning, lack of end-to-end protection, interoperability issues and fault management problems.

### 2.2.2 ITU-T, ASON Control Plane Framework

To overcome the shortcomings of the centralized and manual provisioning process, and to allow automatic switch optical networks, ITU-T introduced its own approach to the problem. The introduction of architecture for an Automatically Switched Optical Network (ASON) [ITU-T G.8080, 2003] by ITU-T Study Group 15 was the second main approach to the problem. As can be seen from the ITU-T documents, ASON is not a protocol or combination of protocols but rather a framework which defines the modules in an optical control plane and the interaction between those modules. According to the definition of ASON provided by the ITU, ASON is a network capable of dynamically switching, adding and removing connections of three different types. Creating and releasing permanent connections, soft or switched connections and soft permanent connections. In ASON the call and connection control are separate and can be accomplished in real time. One of the main advantages of ASON over GMPLS is ASON's capability to add and remove connections without interrupting the already established connections, which is obtained by the separation of call and connection controls in real time. The ASON network control and management is divided into three layers, namely the control plane layer, the management plane layer, and the transport plane layer. The control mechanisms defined by ASON are composed of the connection control (CC) implemented in the Connection Controller Interface (CCI) and the routing controller (RC), which responds to the CC request and can be considered an abstract entity that executes the routing functions. The Link Resource Manager (LRM) is responsible for the management of the SNPP link. Traffic Policing (TP) is another control function responsible for checking the incoming user connections, whether or not it is sending traffic in line with the agreed parameter. The call controller is responsible for supporting the calling and called parties, while the Protocol Controller (PC) maps the interface parameters of the control components onto the messages that are carried by a protocol.

As stated before, the ASON framework defines three different connections to be set up or released, either automatically or with the help of a human operator [ITU-T G.8080, 2003]. The first type of connection is a permanent connection which can be set up and released by the management system or by human intervention. Thus this type of connection does not need control plan intervention and cannot be routed or signaled automatically. The soft permanent connection establishment requires specifying the two already established permanent connections among which a soft connection needs to be established. The soft or switched connection can be established on demand by using the routing and signaling protocols.

The AOSN architecture defines three main interfaces for the interconnection of networks in different domains; the UNI, the I-NNI and the E-NNI.

The ASON enabling mechanisms are the discovery mechanism (Resource discovery, Neighbor discovery and Service discovery), the routing mechanism, the signaling mechanism, the call and connection control mechanism and the protection and restoration mechanism. Figure 2.2 shows the ASON control plane architecture as defined by the ITU-T.

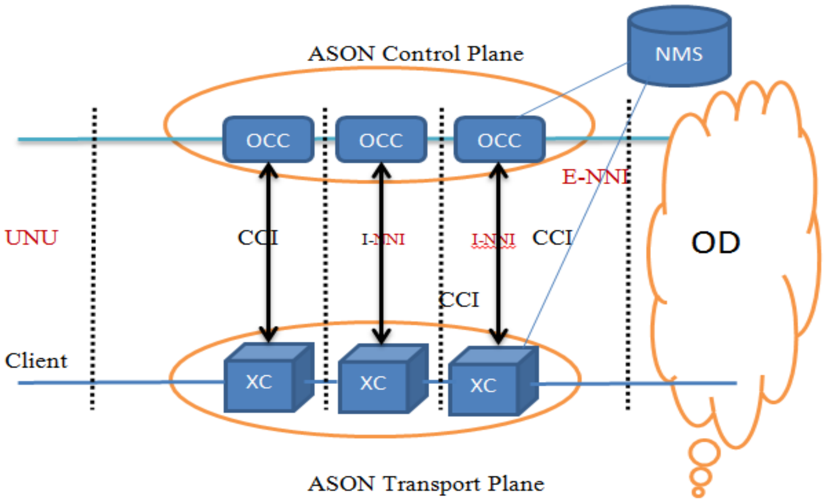



Figure 2.2 ASON architecture (G.8080) and OIF interfaces

Source ITU-T [G.8080], OCC: Optical Connection Controller , CCI: Connection Controller Interface, UNI: User Network Interface, I-NNI: Internal Network to Network Interface, E-NNI: External Network to Network Interface, NMS: Network Managnent Syatem, OD, Other Domain

### 2.2.3 Optical Internetworking Forum (OIF)

The Optical Internetworking Forum is an industry group launched in April 1998 which brings together around 130 companies to foster the development of Internet enabling by optical technologies. To bring the ASON and GMPLS control plan framework into a working solution, OIF combine the ASON architecture with GMPLS protocols. To do so, OIF introduced the UNI 1.0 which was published in February 2004, and which is compatible with the GMPLS protocols. The UNI 1.0 release enabled users to establish optical connection on-demand using the protocols defined by the IETF. UNI release 2.0 added more capabilities to the previous version. Specifically, UNI 2.0 enabled the separation of call and connection control, which is defined by the ASON control plan framework and which can be considered one of the factors that distinguish ASON from GMPLS [OIF, 2003.351, 2006].

There are five defined functions to be supported by the UNI. Those are the connection establishment, connection deletion, discovery of connection status, the discovery of the connectivity between a user, the network and the services and the data plan functionality. Thus two different types of UNI have been defined, namely UNI-C (C stands for client) and UNI-N (N stands for network).

The introduction of the E-NNI enabled the control plane frameworks to be useful in a heterogeneous environment [OIF, 2003.249, 2004]. Heterogeneous networks belonging to different domains exchange their signaling and routing information over the E-NNI. This interface smooth the way for provisioning three kinds of end-to-end connection across multiple domains. The following groups of messages are behind the capability of E-NNI that allow the creation and release of three different types of connection in a heterogeneous environment; connection setup messages, connection release messages, connection query messages and connection notification messages.

### 2.2.4 ITU-T, IETF ASON versus GMPLS

While both the ASON and GMPLS control plan goals are similar, each follows a different approach to the problem. The different approaches of the IETF and ITU can be based on their different historic backgrounds, namely the Internet and telephone networks respectively. Thus, the terminologies used in each document are different, while the meanings are the same.

As can be seen from the previous sections, GMPLS is sufficiently flexible to different architecture. For instance, IETF introduces the Integrated model, the Overlay model, and the Augmented model for the GMPLS control plane framework. In contrast the ITU-T approach follows the Overlay approach with layered routing architecture. To make the GMPLS workable, the IETF has extended previously well-known protocols such as RSVP-TE and OSPF-TE, as well as introducing new protocols like LMP. The ASON framework was lacking in specific protocols to make the ITU-T approach practical. Comparing the GMPLS specific functionalities against the ASON we see that the ASON link manager functions are run by the connection controller and in GMPLS there is no call and connection separation.

In summary both approaches have advantages and shortcomings, which are considered by the OIF and the Common Control and Measurement Plane – CCAMP Working Group efforts. More specifically the ITU and IETF standardization organizations agreed to streamline the architectural differences and to create a common approach, namely the GMPLS/ASON approach which is based on the ASON architecture and used the GMPLS protocols [IETF, RFC 4139, 2005].

## 2.3 Research Support Organizations' Efforts

Research support organizations have been funding multiple projects to improve the efficiency of the existing solution and to generate new ideas to address the problem. In this section we introduce a project that aimed to resolve the management issues of the IP and transport layers.

### 2.3.1 Dynamic Resource Allocation via GMPLS Optical Networks (DRAGON)

The DRAGON project [DRAGON, 2011], which is funded by the United States National Science Foundation (NSF), aimed to develop infrastructures, technologies and the required software to allow the dedication of paths across heterogeneous networks with vendor specific technologies. DRAGON assumes a GMPLS core network, where the switching equipment acts as the Label Switched Routers (LSR). The project demonstrated the dynamic provisioning, inter-domain services routing and end–to-end service provisioning capabilities of a GMPLS core network.

One important feature of the DRAGON project is the development of software required to resolve the issues of the GMPLS control plane. The DRAGON architecture, which defines a Network Aware Resource Broker (NARB), incorporates advanced services from the National Science Foundation (NSF) Middleware Initiative (NMI) program and the Grid services. In the course of the project four software components have been introduced to achieve the project's goals, namely NABRA, the Virtual Label Switch Router (VLSR) which is designed to allow non-GMPLS equipment to participate in end-to-end service provisioning initiated by a GMPLS network, the Application Specific Topology Builder (ASTB) which is used by applications to request connectivity services, and the End-System Agent (ESA) software that runs on the end-system and allows the termination of already provisioned services in the data plane.

### 2.3.2 G-Lambda

The G-lambda project is a joint research project aimed at establishing a standard interface between the network resources and the Grid [G-LAMBDA, 2011]. Enabling an autonomous reservation of the path along optical networks to establish the grid was the main objective of the project. The G-Lambda interface allows users to receive services from different operators using a common interface. During the course of the project, the researchers have developed the required technologies for the operation and management of GMPLS networks to allow the autonomous reservation of path. They introduced a Grid Resource Scheduler (GRS) and a Network Resource Management System (NRM), with whose help they established an autonomous optical path with the required bandwidth. They developed technologies to connect geographically dispersed devices using the appropriate transmission bandwidth. They have demonstrated the capability of their developed technologies in terms of advanced reservation of path, modification of reservation, query of the reservation status as well as the cancellation of reservation.

### 2.3.3 Bandwidth Reservation for User Work (BRUW) Project

The BRUW project, which is part of the well-known Internet 2 project, aims to develop technologies to enable authorized users to reserve network resources across packet switched backbone networks. The goal is achieved by the use of a web-based interface for the user and Layer-3 MPLS protocols. The objective of the project was to replace manual intervention in the process of service provisioning with an automatic process, so as to reduce the service provisioning time and eliminate manual configuration error. In other words, the BRUW project tries to minimize human intervention in the process of service provisioning, automate the service provisioning processes, allow the reservation of resources with no or minimum human intervention, enable users to reliably send large amounts of data over the MPLS networks, and to simplify the reservation processes. They have designed the system with the assumptions that the end user is not a network manager but an authorized user like a researcher. The BRUW architecture uses a powerful authentication and authorization mechanism to ensure the credibility of the request. According to the BRUW documents, one must register for resource reservation to get an ID for accessing the service web page. When Authentication, Authorization and Accounting (AAA) system allows him to request the required bandwidth and the request is accepted, the request will be in queued in the database. When the user's turn arrives, the request will be sent to the MPLS network through the scheduler. The BRUW approach allows the reservation of bandwidth across multiple domains if the domains use the same technology, namely L3 MPLS QoS.

### 2.3.4 IPsphere

As described by Nolle [2005], IPsphere is an inter-carrier automation tool for policy, provisioning and billing. It is aimed to address the business issues of IP and transport networks. IPsphere is a business layer, supplementing the existing IP standards with the capability of exchanging policy-related data to provisioning services over IP based networks. It links the business model and the network architecture instead of dictating a business model, and facilitates business–to-technical linkage between the service providers. IPsphere introduced the term Service Structuring Stratum (SSS), which can be considered another layer on the traditional control plane and the data plane layers. It can handle top-down and bottom-up approaches. In the top-down approach, the network owner enters into a relationship with user to provide a service, while in the bottom-up approach the network operator that wishes to contribute to the pan-provider services defines specific offers called Elements. The Elements can then be offered to all or to a group of administrative owners. According to IPsphere-WP [2006], a service offer is a commercial offer and an Element is an offer for creating a set of service features. There are three phases defined in order to activate a service, called "Components". These are the setup phase, the execution phase and the assurance phase. In the setup phase, the network owner seeks out a contract agreement with the partners to participate in the service, while in the execution phases the owner sends a notice to each partner to create a service on the network. In this phase resources are allocated and the policies are set so as to create a service. In the assurance phase, the partners monitor the agreements, and in the case of misbehavior it will be reported to the owner in the form of an "Alert" signal. IPsphere itself is not a provisioning tool, but it smooth the way for bandwidth on-demand provisioning.

### 2.3.5 Multi-Partner European Test Beds for Research Networks (MUPBED)

MUPBED is another project funded by European Community FP6 with the participation of the well-known industry leaders Ericsson, Telcos, NRENs and universities. According to MUPBED [2011], the partners in the project aim to optimally define network architecture in respect to the research applications, optimizing the interaction of the application platforms with the ASON/GMPLS framework and to efficiently integrate the ASON/GMPLS and IP/MPLS layers. The MUPDRIB architecture is based on principles such as the use of a layered approach, separation of the application and network services, separation of the data, control and the management layers, identification of interfaces, and the partition of the network into administrative domains. The four logical planes defined in the MUPBED project are the Application plane, the Control plane, the Data plane and the Management plane. MUPBED tries to provide a multi-domain and multi-layer solution to the layered approach problem using ASON/GMPLS technology.

### 2.3.6 Next Generation Optical Networks for Broadband European Leadership (NOBEL)

NOBEL is another project funded by European Commission FP6 with the collaboration of network operators, equipment manufacturers and the researchers. The main goal of the project is to find a solution for the creation of an intelligent and flexible optical network. During the course of the project NOBEL followed ten main objectives. The project objectives are; define architectures, guidelines and roadmaps for the optical transport networks, identifying main drivers for the evolution of optical transport networks, studying traffic engineering and resilience mechanisms for a multi-layer, multi-domain environment, describing social and techno-economic aspects of deploying novel intelligent and flexible optical network solutions, evaluating solutions for providing end-to-end QoS, identifying network architecture, concepts and solutions for packet burst switching, proposing the best strategies for end-to-end management and control, finding advanced solutions and technologies for physical transmission, identifying key functional requirements, assessing existing technologies to achieve cost efficiency, and integrating the solutions into existing test beds [NOBEL, 2011].

The NOBEL test bed architecture consisted of an IP/MPLS layer, a transport layer with GMPLS technology and three different domains, and a separate management layer. As illustrated, NOBEL model clearly separated the transport layer (SDH/SONET/ASON) and the service layer (the IP/MPLS and the Ethernet). The project does not aim to integrate the two separate layers but to keep them as overlay networks.

### 2.3.7 Optical Dynamic Intelligent Network (ODIN)

ODIN is part of the Optical Metro Network Initiative project coordinated by ICAIR, aimed at addressing network management issues within the grid environment [OMINIet, 2011]. It can be considered a bandwidth broker controlling a single domain. The ODIN system is able to operate with DWDM and Ethernet switches as well as IP routers. By using TeraAPI, ODIN can accept or reject the user's request. ODIN is also capable of determining and reserving available paths using THOR or DEITI, as well as being capable of notifying the client and reconfiguring the system by itself. Furthermore, the bandwidth broker is capable of creating network topology under the limitations of its administrative domain. In short, ODIN is capable of: accepting or rejecting users' requests, defining a path considering the available resources as well as the QoS requested, reserving the path, notifying clients and collecting topology information.

### 2.3.8 OSCARS

The On-demand Secure Circuits and Advance Reservation System (OSCARS) project, which is funded by ESnet, is also aimed at addressing the need for an automatic system to provision bandwidth on demand [OSCARS, 2011]. The OSCARS system consists of a front end and back end system. The front end system provides the user's interface to the system as well as being responsible for the user's authentication and authorization. The back end system is responsible for reserving the requested bandwidth with the help of a Reservation Manager (RM). OSCARS system has three main components; the Authentication, Authorization, and Auditing Subsystem, the bandwidth Scheduler Subsystem (BSS) and the Path Setup System (PSS). The OSCARS system allows on-demand bandwidth provisioning in both single domain and multiple domains working under different administrative boundaries.

### 2.3.9 NOBEL 2

NOBEL2 or NOBEL Phase 2 was the continuation of the NOBEL or NOBEL1 project. The main goals of NOBEL2 was to carry out the analysis and feasibility study and experimentally validate new network solutions for a flexible, scalable and reliable optical network enabling broadband services [NOBEL2, 2011].

While the project gave an insight into network evolution, the ASON/GMPLS control plane tests remain limited to a single domain. The project document mentioned that many issues may arise when considering tests for a multi domain scenario.

### 2.3.10 Scalable, Tunable and Resilient Optical Networks Guaranteeing Extremely-high Speed Transport (STRONGEST)

To provide a solution for the bottlenecks of today’s transport service providers, namely addressing the growing demand for bandwidth, the high operational cost, limited scalability and to guarantee the end–to-end QoS, the European Union recently funded another project called STRONGEST [STRONGEST, 2011]. The aim of the project is to design and demonstrate an evolutionary ultra-high capacity multilayer transport network, capable of handling a Gbit/s access rate in a multi-domain, multi-technology control plane environment.

## 2.4 Telecommunication Industry Vendors' Efforts

Vendors have also tried to imbed new functionalities into devices so as to address network management issues, as well as to improve the value proposition of their products.

### 2.4.1 Cisco

Cisco introduced two routers to allow the convergence of IP and DWDM layers in the core network. According to Cisco IP over DWDM [2007], Cisco Routers CRS-1 and Cisco ONS 15454 allow the integration of management tasks between the IP and DWDM layers, which consequently simplify and reduce the network's operational cost. The efficiency gain is achieved by the implantation of tools such as troubleshooting and wavelength provisioning. As claimed, service providers working under segmented operational organizations can still take advantage of a unified management system while providing access to segmented operational groups when needed.

### 2.4.2 Ericsson

Ericsson introduced a network management product to allow IP transport over an optical network. According to Ericsson IP-Transport NMS [2011], the IP Transport NMS product allows the smooth migration to the next generation of IP networking technology, with the features such as self-healing, intelligent VPN provisioning and the full management of Ethernet services. It is capable of managing a pure TDM network, Pure IP network and pure Ethernet optical transport with or without WDM connectivity.

The IP Transport NMS network management system allows end-to-end service oriented management, including operation support systems integration in both layers. The product is designed for packet switched and circuit switched networks.

### 2.4.3 Nokia Siemens and Juniper

According to Nokia, Siemens and Juniper [2009], the leaders of high performance networking are combining their efforts to bring complementary technologies closer to each other in order to provide a better IP optical integration solution.

Juniper has world class IP routing expertise, while the Nokia Siemens group has expertise in WDM technologies. The two industry leaders aim to provide a highly flexible, reliable and cost-effective way to manage the growing volume of data, voice and multimedia. Their objective is to provide a better and more cost-effective solution for 10G, 40G and 100G IP over DWDM, with integrated management based on control plane frameworks.

# Chapter 3. Techno-Economic Evaluation of Proposed Control Plane Frameworks

## 3.1 Introduction

The aim of this chapter is to technically and economically evaluate the proposed control plane frameworks in order to answer the question why the standardization organizations' solution to the problem of network management and network control was found not to be a desirable solution for the operators. Furthermore, by technically and economically evaluating the GMPLS control plane we would like to develop our approach, namely the mediator model between the IP and transport layers in the Internet.

The IETF control plane framework (GMPLS) and the ITU-T control plane framework (ASON), which are discussed in the first chapter, have received huge interest in the industry as well as in the research community. The expectations of those two main standardized frameworks were enormous, becoming the reason for their wide support among telecommunication vendors. Major telecommunication vendors such as Siemens and Ericsson imbedded GMPLS technology into their products, and even introduced better versions such as the S-GMPLS introduce by Cisco.

Unfortunately despite strong support from both the standardization organizations and the vendors, the success of control plane framework deployment was found to be less than expected.

The control plane framework's technical challenges have been discussed by many scholars. The most recent [Narayanaswamy, 2011] remarks about the GMPLS is the evidence of challenges the control plane frameworks face.

In order to offer testimony as to why network operators are not willing to deploy or use all the functions that the control plane framework can theoretically provide, in this chapter we calculate the GMPLS control plane deployment cost and check its cost efficiency, which is claimed to be 50% in terms of operational cost.

To do so, we start the discussion with a short technical evaluation of the proposed frameworks. Afterwards we evaluate the economic factors, namely the deployment cost and the cost efficiency of the GMLS control plane framework. To do so, we propose a cost estimation model with the help of which we test the claims of previous research which found an operational cost reduction of 50% in networks with the control plane. We conclude this chapter with a short summary of our findings.

## 3.2 Literature Review

The control plane frameworks were developed on the basis of network operators' requirements, which have been assessed by the Scorpion project [SCORPION, 2003].

The Scalable Optical IP Transport Network (SCORPION) project aimed to combine the functionality of IP and MPLS technologies with the recently emerged Optical Transport Network (OTN). In the course of the project, SCORPION assessed the carrier requirements for providing optical transport services to the IP layer. Their findings provide an insight into the technical requirements, such as visibility, network management, reliability, addressing, traffic management, and QoS, which was then used by the standardization organizations to address the transport network operators' requirements in the control plane framework.

However, apart from these technical requirements, factors such as current and future application demand and application requirements, deployment challenges, cost efficiency, and return on investments are important to be considered when providing a desirable solution to the problem.

The efficiencies of GMPLS and ASON compared to traditional systems have been extensively studied by scholars. The ASON/ASTN cost efficiency was assessed by Chahine [2004]. The author analyzed the ASON/ASTN framework quantitatively and came to the conclusion that the technologies are promising and provide a significant reduction in operational costs. They compared the traditional way of service delivery with the new ways proposed by the ASON/ASTN. According to the findings, the traditional way of service delivery involves sales, administration, project management and network operation departments. The normalized cost of service delivery in traditional systems found to be 3.97, while in the case of the automated service delivery process only administration costs will accrue, resulting in a normalized cost per service of 0.8. After adding the side works costs, which include human capital costs, the estimated operational cost savings showed 51% per service in the case of ASON/ASTN.

The GMPLS control plane influence on the network providers' operational cost was studied by Pasqualini et al. [2005]. In their study, they considered the impact of GMPLS technology on the continuous cost of infrastructure, routine operation, reparation, operational network planning and marketing costs. According to their findings, GMPLS control plane deployment has a deep impact on the service delivery process, which is simplified by the use of UNI. They also come up with a 50% OPEX reduction in the case of the GMPLS capable network compared with the traditional service provisioning process in traditional networks.

The influencing factors of new technologies, namely the control plane framework's influencing factors are discussed by Verbrugge et al. [2006]. The factors they mentioned are; the resilience mechanism which has a strong impact on repair cost, and service provisioning which is automated in the case of control plane frameworks, compared to the traditional manual process of setting up a network connection. Apart from the above-mentioned new technology influencing factors, they also discuss the role of new technology in allowing new services over the network.

In a case study presented by Verbrugge, Colle and Pickavet [2006] the authors calculated the total expenditure for a German reference network, where for the traditional network they considered 1+1 protection, while shared protection was assumed for the GMPLS capable networks. Their findings suggest that the total network cost in the case of GMPLS is 79% of the total traditional network cost.

The challenges faced by operators while exploiting the control plane frameworks have been highlighted by many scholars [Zafar, 2007; Ichiro, 2007; Narayanaswamy, 2011]. The most recent and important remarks on GMPLS control plane usage was made by the Narayanaswamy, Vice President of Network Architecture for Reliance Globalcom. He asked carrier representatives in the conference to raise their hands if they actually used GMPLS, all he got were a couple of wavy-handed.

Shukla, a principal technologist at Verizon Communications Inc. (NYSE: VZ), which was also participating in the conference, mentioned that GMPLS deployment is a complicated chore for network operators. "When we are going to change the control plane, we are changing the process. Changing the process in the network is slow, because there is already a process in place which works" [Shukla, 2011].

The GMPLS control plane proposes centralized network management and network control, while the schism between the IP side and the transport side of the company is a big issue in the path for the deployment of a centralized approach, which consequently makes companies reluctant to exploit all features of GMPLS [Ichiro, 2007]. The complicated operation and maintenance of the GMPLS-based IP optical network is also mentioned by Zafar [2007].

There are three major potential issues with respect to GMPLS-based network operation from a service providers' point of view. Those are the GMPLS requirements for highly flexible and granular policies, the ineffectiveness of dealing with unexpected incidences and the difficulty of managing the new GMPLS-based services [Ichiro, 2007].

As can be seen from the above-mentioned statements, the economic evaluation of control plane frameworks is not reflected in the technical evaluation. To provide a more realistic GMPLS control plane deployment cost estimation we need to define the network operator's operational expenditure and the capital expenditure.

Nea and Chang [2001] classified the network operators' operational cost into direct costs and indirect costs. In the direct OPEX they included all costs that have a direct impact on production, such as the configuration cost, fault management cost and workforce management cost. Indirect costs are defined as the cost for the supporting tasks, such as headquarter rental, heating and cooling costs.

The activity-based network operation costing methodology was discussed by Eun, Gi and Jea [2011]. In their study, they the linked the direct and indirect operational costs into main activities in the network, then they specified the related department and defined the cost for each department. According to the authors, the methodology they proposed allows the cost causalities to be easily located, it supports decision making and allows efficient operation. The drawbacks listed for activity-based costing are the high cost, the difficulty of designing the cost model, the current research cost, the expense of supplies and the space rental cost.

The local telecommunication network cost was studied by Christian and Kenneth [1999]. They applied a comparison methodology on the spanning trees and the HAI Model. Their findings suggest that the HAI model underestimates the network cost. They mentioned the consequences of underestimating network costs, and they claim that after their findings HAI Consulting Inc. revised the model.

Application of the parametric cost estimation model to the telecommunication network was studied by Swadesh, Johan and Mohammad [2009]. According to the authors, the parametric cost estimation proved its efficiency for analyzing complex systems. The authors modeled the telecommunication network cost based on distance, bandwidth, geographical terrain and technology. They claim that the model is useful for addressing issues of interconnection pricing for long distance communication.

Application of cost models in Latin American and Caribbean countries was studied by Klein [2007]. The author in this study discuss the historical cost, the forward looking costs, the current costs, the fully distributed costs, the activity-based costs and the long run incremental costs. Also discussed were the concepts of access deficit, total element long run incremental cost, standalone cost and unbundling.

The impact of technological changes on the cost structure were discussed in EU Recommendation [2005], where it was mentioned that the limited scope of existing static cost models mean these models are not useful for taking into account technologically converged systems. It was also noted that the new environment needs new ways of thinking and seeing things.

The network operators' operational and capital expenditures are studied in detail by Chahine et al. [2004], Pasqualini et al. [2005], and Verbrugge et al. [2005; 2006]. They provide a classification of telecommunication operators' cost factors. They also present models for cost calculation which are presented and tested by the case studies discussed in the previous paragraphs.

In order to provide a more realistic picture of control plane framework deployment cost, in the next subsection of this chapter we derive the telecom operators' expenditure which will help us construct a cost model to evaluate the deployment cost of new technologies.

## 3.3 Telecommunication Operators' Expenditure

Similar to all other industries, the telecom operators' expenditure can also be classified into two main parts, Operational Expenditure (OPEX) and Capital Expenditure (CAPEX). Assessing the telecommunication operators' cost structure requires knowledge of the telecommunication industry OPEX and CAPEX. To meet our goal, namely to provide an economically clear picture of migration to the control plane framework, in the next section we specify the operator's OPEX and CAPEX parameters so as to develop a cost estimation model for the deployment of new technologies in networks that are up and running.

### 3.3.1 Telecom Operators' OPEXs

The financial dictionary defines operational expenditures as the company's expenses related to the production of goods and the services, such as wages and the cost of raw material. OPEX does not include any other expenses that are unrelated to production whist essential for the operation [Farlex Financial Dictionary, 2011]. Operational expenditure is "an ongoing cost for running a product, business or system" as stated by Maguire [2008]. The OPEX complements the CAPEX [Aswath, 2004].

The two major contributors of telecommunication operators' OPEX as defined by Verbrugge [2005] are the OPEX that are directly related to the production of goods or services, and the OPEX which is not directly related to production. He also distinguished between OPEX that are specific to the telecom industry.

Based on the above-mentioned literature, the telecommunication operators' operational expenses can be summarized as follows;

- Continuous cost of infrastructure (including but not limited to)
  - Space costs
  - Power
  - Heating and cooling
- Maintenance costs (including but not limited to)
  - Stock management cost (keeping track of available resources, etc.)
  - Software management cost (keeping track of versions, updates, etc.)
  - Security management cost (keeping track of violations to access the system, etc.)
- Reparation costs (including but not limited to)
  - Problem diagnosis (if outsider efforts involved)
  - Transportation cost technician to reach the area
  - Actual fixing costs (including the cost of testing)

- Service provisioning costs (including but not limited to)
    - All technical costs (related to service provisioning process activities)
- Pricing and billing costs (including but not limited to)
    - Technical cost of sending bills to customers
    - Technical cost of collecting information on service usage
    - SLA charges
- Planning costs (including but not limited to)
    - Planning updates
    - Optimization costs
- Marketing costs (including but not limited to)
    - Technical costs of promoting services
    - Awareness costs
- Administration costs (including but not limited to)
    - Overhead costs
- Human capital costs (including but not limited to)
    - Wages
    - All costs related to human capital training
    - Tools and transportation for training.

We consider the human capital cost to be separate from the others. This is because human capital expenses are involved in all the process and it cannot be specifically defined how much time has been spent by an individual on a specific purpose. Furthermore, even if one can specifically define the proportion of wages to every specific action it is still necessary to add the rest, which is the non-productive time of each employee. So we decided to keep the human capital cost separate from all others. We include all costs related to human capital training in the human capital cost, this is because we believe that the purpose of this kind of expense is to improve the human capital ability and it should therefore be covered here rather than in the overhead cost.

Based on the OPEX components specified in the previous paragraphs, we derived the telecommunication networks' OPEX formula as shown in Equation (1).

$$OPEX = \sum_{i=1}^{k_I} C_{I_i} + \sum_{i=1}^{k_{Ma}} C_{Ma_i} + \sum_{i=1}^{k_R} \left(C_{R_i} * N_{R_i}\right) + \sum_{i=1}^{k_{SPM}} \left(C_{SPM_i} * N_{SPM_i}\right) +$$

$$+ \sum_{i=1}^{k_{Pl}} C_{Pl_i} + \sum_{i=1}^{k_{Mr}} C_{Mr_i} + \sum_{i=1}^{k_{BP}} C_{BP_i} + \sum_{i=1}^{k_H} C_{H_i} + \sum_{i=1}^{k_A} C_{A_i}$$

Equation (1)

In Equation (1), CIi represents the continuous expenses related to the infrastructure (e.g. electricity cost and cooling cost), CMai represents the cost of maintenance (e.g. upgrading software and hardware), CRi the repair cost, and CSPMi the service provisioning management cost. CPli denotes the planning activity cost, CMri the marketing cost for different services, CBPi the billing and pricing cost, and CAi the administration cost. Finally, CHi represents the cost of human resources (e.g. wages and training). NRi and NSPMi denote the frequency of the actions. kI, kMa, kR, kSPM, kPl, kMr, kBP, kA, and kH indicate the number of different types of OPEX cost factor.

### 3.3.2 Telecom Operators' CAPEXs

According to the Farlex Financial Dictionary [2011], an investment is considered to be capital expenditure if the aim of the investment is to acquire or upgrade physical assets, like property or equipment. In terms of accounting, capital expenditures are the expenses for new capital or an investment that increases the useful life of already existing property. In order to return the investment on the CAPEX, investors divide the cost of expenditure over the useful life of the properties or equipment and take it into account when pricing the goods or services. The cost is deducted each year until it becomes zero, which means that the equipment or the property needs to be replaced or renewed.

In general, CAPEX describes the cost of fixed assets. Telecom operators' CAPEX directly includes the cost of infrastructure related to network operations (e.g. network management systems) and those that indirectly support the operation of the network (e.g. places of residence for staff). Thus it is subject to depreciation.

Telecom operators' CAPEX can be classified into three major groups. The first group comprises the total cost for the information and communication (IC) equipment (e.g. switches routers and cables, first time installation cost). The second group includes the total cost of properties that are directly or indirectly involved in the production (e.g. buildings and houses). The last group is the total cost for the telecommunication industry's business licenses. Equation (2) describes three major components of telecom operators' capital expenditure.

$$CAPEX = \sum_{i=1}^{k_E} \left( C_{E_i} * N_{E_i} \right) + \sum_{i=1}^{k_P} \left( C_{P_i} * N_{P_i} \right) + \sum_{i=1}^{k_L} \left( C_{L_i} * N_{L_i} \right)$$

Equation (2)

In Equation (2), CEi, CPi, and CLi represent the cost of a specific type of item. NEi, NPi, and NLi represent the number of each specific type of cost item. We consider kE, kP, and kL types of equipment, property, and license.

It is worth mentioning here that, while some authors consider the first time installation cost to be part of OPEX, we differentiate between the first time installation cost and the installation cost of hardware and software during the maintenance or planning activities period. The reason behind considering the first time installation cost as a sub-component of CAPEX is the reality on the ground. More clearly, in today's practices almost all software required for the normal function of a device is embedded in the system. Furthermore, equipment vendors include the first time installation cost in the price of hardware when pricing the devices. The final reason is the consideration of the frequency of this action, which is accrued only once (when a company buys the devices). Thus based on the above points, we cannot include the first time installation cost in the telecom operators' operational cost.

## 3.4 Telecom Industry Specific Characteristics

To ensure that we are considering the telecommunication industry specifics in our techno-economic evaluation, in this section we highlight some very important factors that need to be taken into account when studying telecommunication industry techno-economics.

There is a consensus among scholars that the telecommunication industry is among the capital intensive industries. This is because the equipment and the technologies used in the information and communication sector are expensive. The second reason is that, in order to offer a service, telecom operators must reach the user either via a wired or wireless connection, which increases the cost of the infrastructure.

Furthermore, the information and communication industry's equipment has a long useful life time, which makes it more difficult to acquire new technologies. According to the estimation of the Internal Revenue Manual (IRM) published on January 10th 2010, the equipment of the information and communication industry has on average a useful life time of 7 years [Internal Revenue Manual, 2010].

Network operators need to accept drastic changes in the network to acquire new technologies, as well needing to consider large investment in the network infrastructure. The above-mentioned facts make it hard for this sector to accept changes, while network operators' are still willing to migrate to other technologies to reduce their operational costs and to improve network efficiency. For a network which is up and running, acquiring new technology means removing old technologies from the service which are still useful.

In general, to acquire new technologies, telecommunication network operators have at least three options. For instance, if a telecommunication operator is willing to deploy a new network management system (to ease network operation and to reduce operational expenses), he/she can either replace all non-compatible devices with the new system, or upgrade all eligible network devices for compatibility with the new system. The third option is to acquire new technology by gradually replacing or upgrading network devices.

As stated previously, telecommunication equipment is costly. Replacing all network devices that are not compatible with new technologies is a costly decision, not only because of the new hardware cost but also because of the hardware that needs to be replaced while still being useful and not having completed its useful life.

Similarly, as also stated by Kumaki [2006], we should not expect all network devices to be eligible for upgrade. This means that when upgrading the network, we must consider the case that a percentage of the network devices will need to be replaced because they cannot be upgraded. The second reason for replacing network devices and not upgrading them is the amount of useful time left. Of course, it is not a reasonable to invest more in network devices which need to be replaced in one or two years. For example, in order to upgrade a network device to support the GMPLS protocols one needs to invest at least 100 K Euros, which is approximately 80% of the total cost of the new equipment. Thus if the device only has two years left of it is useful life time, then out of all new investment only 30% of the investment will be returned and 70% will be wasted because the device will be replaced after two years. Thus, we will consider all above-mentioned specifics of the telecommunication industry when developing a cost estimation model for the GMPLS control plan deployment.

## 3.5 Cost Estimation Model

Our intention behind the discussion in the previous section (telecommunication operators' operational and capital expenditure) was to drive a mathematical module so as to estimate the migration cost of new technology. We also aimed to test the controversial claims of previous authors who claim GMPLS deployment will lead to a 50% reduction in operational cost over the network.

Of course the OPEX and CAPEX are the two main components of any cost model. But in our specific case, the aim of which is to analyze the deployment cost of new technologies for existing networks, these two components are not enough to accurately estimate the deployment cost. As stated previously, for a network which is up and running we must consider the case that some percentage of the network's equipment will be completely replaced while upgrading the network. This means we have to take into account the remaining depreciation cost of the hardware that must be replaced while still useful. Equation (3) represents the migration cost estimation model for a network which is up and running.

$$C_{t-n} = \sum CAPEX + \sum OPEX + \sum Dep.cost$$

Equation (3)

Equation (3) extends the CAPEX and OPEX discussed in the previous section and adds the value of the equipment that has not fully depreciated but needs to be replaced. This additional factor allows us to express the cost Ct-n for migrating from an old technology to a new one (i.e. from a traditional network to a GMPLS-capable network).

While moving to acquire new technologies, not all OPEX and CAPEX elements shown in Equations (1) and (2) will be accrued. And so we will multiply by 0 the cost factors of CAPEX and OPEX which will not be involved in the process of migration from Equation (4), which is the extended version of Equation (3).

$$C_{t-n} = \sum_{i=1}^{k_E}(C_{E_i} * N_{E_i}) + \sum_{i=1}^{k_P}(C_{P_i} * N_{P_i}) + \sum_{i=1}^{k_L}(C_{L_i} * N_{L_i}) + \sum_{i=1}^{k_I} C_{I_i}$$
$$+ \sum_{i=1}^{k_{Ma}} C_{Ma_i} + \sum_{i=1}^{k_R}(C_{R_i} * N_{R_i}) + \sum_{i=1}^{k_{SPM}}(C_{SPM_i} * N_{SPM_i}) + \sum_{i=1}^{k_{Pl}} C_{Pl_i}$$
$$+ \sum_{i=1}^{k_{Mr}} C_{Mr_i} + \sum_{i=1}^{k_{BP}} C_{BPi} + \sum_{i=1}^{k_H} C_{H_i} + \sum_{i=1}^{k_A} C_{A_i} + \sum_{i=1}^{k_d} C_{d_i}$$

Equation 4

Equation (5) shows a cost model for a move from an old technology to a new one (COtoN). We consider the equipment cost CEi to cover the cost of the hardware and software that needs to be replaced. The maintenance cost CMa, which covers the cost of upgrading the network hardware and software, can be considered an irregular maintenance cycle. The human resource cost CHi covers the cost of training network engineers so that they can operate the new technology. Cdi covers the depreciation costs of the hardware and software that need to be replaced while not being fully depreciated (i.e. this equipment cannot be used up until the end of its expected life time).

$$C_{OtoN} = \sum_{i=1}^{k_E}(C_{E_i} * N_{E_i}) + \sum_{i=1}^{k_{Ma}} C_{Ma_i} + \sum_{i=1}^{k_H} C_{H_i} + \sum_{i=1}^{k_d} C_{d_i}$$

Equation 5

The cost of technology selection and the bidding process, which is necessary for migration, is assumed to be part of the wages and the administration costs. This is because we know that the network operators are not paying extra money to their employee to process a bid. So the human cost of the technology selection and bidding process is covered by the wages. Other costs related to the technology selection and bidding process, such as the bid announcement are very small compared to the bid price, and can be considered to be covered by the administration cost.

## 3.6 GMPLS Deployment Cost and its Benefits

Based on the fact that every specific investment must be justified by their technical and economic benefit, which also depends on the goals of the investor, the GMPLS control plane deployment must also be justified by its advantages over the traditional network control system.

### 3.6.1 GMPLS Control Plane Deployment Cost

To describe the cost of acquiring a GMPLS control plane, we present a specific case study in which a transport network provider with WDM technology is willing to upgrade their network to a GMPLS control plane.

The main objective of this paper is to estimate the GMPLS technology migration cost. By using the cost model developed in the previous section, we try to estimate the cost of the GMPLS framework deployment in the networks with 10, 20, 30 and 40 nodes. Each network uses WDM technology and a 2.5 Giga bit/sec leased line in the transport layer.

For our case study, the network service provider is upgrading the existing network hardware and software to move from one type of network management system to a more sophisticated one. This allows the network operator to upgrade the network step by step. It also requires less CAPEX, as the cost for upgrading a network device is much lower than its complete replacement. As also mentioned previously, not all network hardware and software can be upgraded to support the GMPLS protocols. Consequently, we must assume that some portion of the existing hardware, which did not reach the end of its depreciation period, needs to be replaced.

Considering the relatively rapid change in technology, it is reasonable to expect that every replacement in the network leads to acquiring new devices with an improved level of capability. Based on this, and as a starting point in our case study, we assume that 80% of the network devices have sufficient capabilities to be upgraded. The remaining 20% needs to be replaced because of incapability or non-eligibility to be upgraded to the GMPLS control plan. Among those 20%, half of them did not reach the end of their life time (i.e. depreciation period). The values can be found in Table 3.1, case a).

We assumed the minimum value of 20% replacement of network devices, as network operators replace their network devices regularly based on their planning activities and the depreciation period. They also replace network devices which are going out of service. Of course, a rational manager will replace the network hardware to more advanced devices which may have the capability of being upgraded to support more advanced protocols.

Table 3.1. Percentage of replicable hardware and number of equipment replaced

| Number of nodes in the network | Number of hardware that is not upgradeable and needs to be replaced | | | | | | | | Total number of hardware replaced if 20%, 30%, 40%, and 50% need to be replaced, respectively | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hardware that has been depreciated | | | | Hardware that has not been depreciated | | | | | | | |
| | a) 10 % | b) 15 % | c) 20 % | d) 25 % | a) 10 % | b) 15 % | c) 20 % | d) 25 % | 20 % | 30 % | 40 % | 50 % |
| **10 nodes** | 1 | 1 | 2 | 3 | 1 | 2 | 2 | 2 | 2 | 3 | 4 | 5 |
| **20 nodes** | 2 | 3 | 4 | 5 | 2 | 3 | 4 | 5 | 4 | 6 | 8 | 10 |
| **30 nodes** | 3 | 4 | 6 | 7 | 3 | 5 | 6 | 8 | 6 | 9 | 12 | 15 |
| **40 nodes** | 4 | 6 | 8 | 10 | 4 | 6 | 8 | 10 | 8 | 12 | 16 | 20 |

In the same way, as described for the case of 20% of replaced hardware (i.e. case a) in Table 3.1, we set the actual number of hardware to be replaced for three further cases. These cases determine that 30%, 40%, and 50% of the hardware has to be replaced. For these cases, Table 3.1 shows the actual number of hardware to be replaced for the networks with 10, 20, 30, and 40 nodes.

For our calculation, and because the network device costs are negotiable, we used the data presented by Verbrugge et al. [2005]. Additionally, we also assume that the cost of GMPLS control plan software will be equivalent to an un-equipped OXC. The values used are presented in Table 3.2.

Table 3.2. Equipment and Software Prices for WDM Networks
Based on Findings of [Verbrugge, et al. 2005]

| Equipment type | Footprint (ETSI) | Price K Euro |
|---|---|---|
| WDM Line system (40 Lambda) | 3 Racks | 12.00 |
| Optical Amplifier | 0.25 Racks | 7.90 |
| SR Transponder (2.5 Gbps) | Inserted in OXC | 2.00 |
| LR Transponder (2.5 Gbps) | Inserted In OXC | 2.50 |
| Unequipped OXC (512 port) | 3 Racks | 100.00 |
| GMPLS software | One license | 100.00 |

Furthermore, based on the fact that the hardware and software vendors provide discounted rates for the purchase of large quantities of hardware and software licenses, we assume that the discounted prices vary between 5% and 10% of the total equipment price, depending on the amount of equipment ordered. Similarly, the per-person training cost also depends on the number of trainees. To capture this effect, we assume that the percentage of discount for training varies between 10 and 20% depending on the number of trainees. We consider the per-person training cost to be as high as 0.5% of the hardware cost.

Based on these values, Figure 3.1 presents the results of our cost model calculation for networks with 10, 20, 30, and 40 nodes. The horizontal axis in Figure 3.1 shows the percentage of hardware that needs to be replaced within a network, while the vertical axis shows the GMPLS deployment costs for these networks.

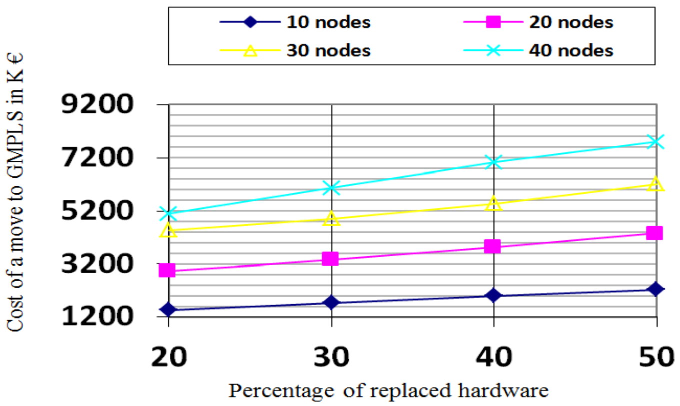



Figure 3.1 Cost estimation for migration to the GMPLS enabled network

The results of our cost model calculation (Figure 3.1) suggest that in general the deployment cost of the GMPLS control plane mostly depends on the amount of hardware that needs to be replaced, as well as the number of nodes in the network. Specifically, the GMPLS control plane deployment cost increases as the number of nodes in the network increases. It also increases as the amount of hardware replaced increases.

Figure 3.2 shows the GMPLS control plane estimated deployment cost per node. According to this figure, the pre-node migration costs are much lower in the case of a network with a larger number of nodes. However it increases as the number of nodes in the network reduces. In contrast, the pre-node cost increases as the percentage of replaced hardware in the network increases (Figure 3.2 – network with 10 nodes, 20 nodes, 30 nodes and 40 nodes with 20%, 30%, 40% and 50% replaced hardware).

Our calculations also suggest that the GMPLS deployment cost per node will decrease if more nodes need to be upgraded in the network. For example, Figure 6 shows that the cost per node for a network with 40 nodes and with 20% replaced hardware is 19K € less than the cost per node for a network with 10 nodes and 20% replaced hardware. This can be interpreted as the effect of the discounted rates on the hardware, software and training.

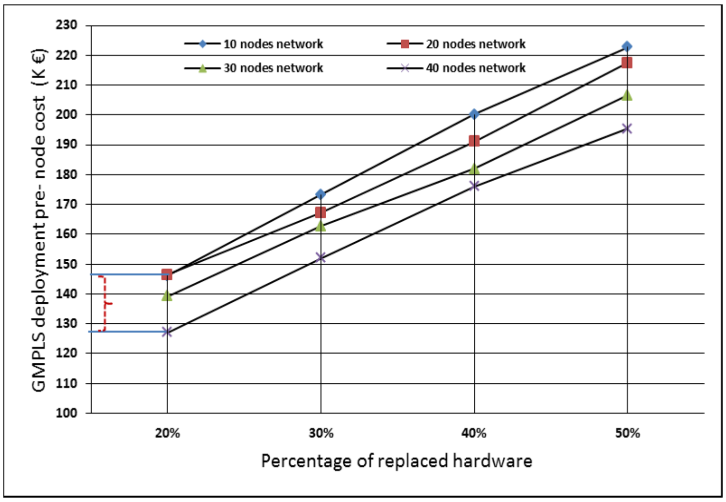



Figure 3.2 Per-node cost estimation for migration to GMPLS enabled network

The four bar graph at the right-hand side of the figure depicts the migration cost to the GMPLS enabled network, without considering the depreciation cost of capital, while the left-hand side shows the migration cost considering the depreciation cost of the capital. It is important to note that the figures on the right-hand side can also describe the cost of GMPLS technology for a new competitor, as the depreciation cost of capital for the new competitor is equal to zero.

Figure 3.3 shows the bias of the cost estimation when the depreciation cost of network hardware that is subject to be replaced while not fully depreciated is not considered. For instance, as also can be seen from the figure above, for a network with 40 nodes and 20% replaced hardware (the upper line left-hand side of both graphs) the difference is equivalent to 448 K Euros compared to the same line on the right-hand side figure belonging to the same network.

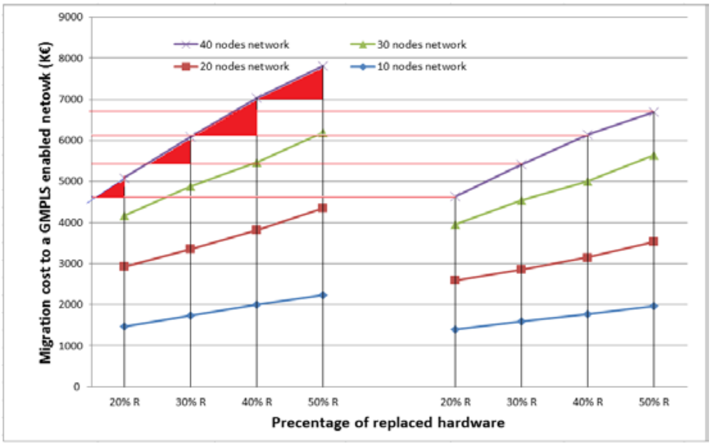



Figure 3.3 Cost estimation for migration to the GMPLS with and without the depreciation cost of capital

Investment can always be justified if the technology deployment leads to economic gain expected. To estimate the cost benefits of this move, in the next sub-section of this dissertation we will evaluate the GMPLS technology cost and its economic gains in terms of service provisioning for a network which is up and running.

### 3.6.2 GMPLS Control Plane Cost–Benefit Analysis

The GMPLS control plane operational cost–benefits are presented by Chahine, Kirstadter and Pasqualini et al, [2004], where the authors claim that GMPLS capable networks have 50% less operational cost than networks with the traditional network management and network control system. The claim looks controversial, because the statements of the LightReading Conference participants suggest that network operators are not willing to deploy the GMPLS framework, or if they have deployed it they are not using all its features [Narayanaswamy, 2011].

With the aim of answering the question, “Why network operators are not willing to migrate their network to a GMPLS capable network?” we calculate the GMPLS control plane cost efficiency based on its involvement in the process of network management and network control. But before discussing our control plane cost efficiency estimation approach, we briefly look at the findings of other scholars that have found huge OPEX reduction in the case of GMPLS enabled networks.

#### 3.6.2.1 Previous Studies

The technical and economic efficiencies of control plane frameworks have been studied by many scholars. There is a consensus among the scholars that the control plane reduces network operational costs and introduces intelligence into the network, which allows new services to be run over the network. Theoretically GMPLS provides what network operators would like to have [Narayanaswamy, 2011]. However, practice shows that network operators are not satisfied by GMPLS for the presumptive reasons discussed previously. In this section we would like to highlight the approach of the scholars that found huge OPEX reductions in GMPLS capable networks.

The ASON/ASTN control plane operational cost reduction was presented by Chahine [2004]. The findings of the author suggest that by deploying control plane frameworks, network operators can reduce the OPEXs by 51% to 81% for different processes. According to the author, the calculations considered five types of service. Those are the service offer, service delivery, cease process, move and change, and repair process. As can be seen from the definition of the service they provided, the service offer is the process of SLA setup which is the same for the both types of network, as suggested by the author (Figure 3 – traditional service offer, SLA negotiation). The "move and change" is the same as the SLA setup and service delivery. Furthermore, Chahine has arrived at a 50% OPEX reduction for the GMPLS capable network compared with the traditional network, while the frequency of service delivery was not considered.

Pasqualini et al. [2005] also claim that the deployment of GMPLS leads to a 50% OPEX reduction. While their findings also suggest that GMPLS impacts more on service delivery than any other, they also did not consider the frequency of service request which may have biased the result.

The findings of Verbrugge et al. [2005] suggest that the total network cost for the GMPLS enabled network is 21% less than the total network cost for a traditional network, while the ratio of OPEX/CAPEX is the same for both. The result is challenging, as the authors clearly state that the GMPLS software cost is equivalent to an unequipped OXC, which is 44% of the total equipment cost. According to the authors, the main difference is derived from the protection mechanisms, while the same kind of protection (shared) is also provided by a traditional WDM network.

Kirstadter et al. [2006] quantitatively studied the impacts of ASON/GMPLS on OPEX. Their findings suggest that ASON/GMPLS deployment may lead to a 50% OPEX reduction, while they also found that ASON/GMPLS mostly impacts on the service provisioning process. The authors do not considered the impact of frequency of service provisioning in their study.

In short, the findings of all the above-mentioned studies suggest that the control plane frameworks' deployment strongly impacts on the service provisioning process cost. It also impacts strongly on the service offer cost, if the service is provided on-demand (with a fixed price).

Considering the fact that network operators are not using the on-demand delivery of the service, so far the efficiency of the control plan framework is limited to the service provisioning process, the frequency of which is very important for consideration when investigating control plane cost efficiency.

#### 3.6.2.2 Control Plane Cost–Benefit Estimation Approach

In our study we will look at GMPLS control plane cost efficiency from a different angle. More specifically, we estimate the GMPLS cost efficiency based on the services on which it has a strong impact. In general, control plane frameworks developed and standardized by IETF and ITUT are aimed at easing the service provisioning process between the layer and the domain on the Internet, which is currently manual, error prone, time-consuming and costly.

The findings of previous researchers also suggest that the GMPLS control plane has a strong impact on three main services, namely service offer, service delivery and cease process. All three mentioned services are directly related to the service provisioning process. Among the above-mentioned three services, the service offer called Service Level Agreement (SLA) setup is hard to automate as demanded by the GMPLS. This is because network operators need to assign a fixed cost for the bandwidth, which is not desirable.

While on-demand provisioning is a reality for the future, for now there is not enough application as well as desire for providing bandwidth on-demand services. One of the main issues of on-demand provisioning is the complexity of the mechanism which may result in destabilizing the network. As stated by Ping and Lyndon [2011], the current approaches of on-demand services are based on management interfaces to vendor-specific equipment. This approach requires the redesign of supporting applications for each and every domain. Furthermore, the interfaces currently used in the control plane frameworks such as UNI provides minimal security and functionality, because was originally designed for a peer relationship.

According to IETF Interne draft [2011], BoD applications must be designed for a particular technology which limits its usage. Similarly an important fact is that the carrier providers are not willing to lose control over the network and allow users to change the bandwidth as they wish.

The service cease is another process which is said to be impacted on by the GMPLS control plane. While it is clear that the control plane frameworks allows the automatic setup and release of a connection, the service cease process in traditional systems does not involve multiple departments and can be executed by just interring into the system and stopping the service. Although this is currently a manual process, its cost is negligible compared to the service provisioning process.

In reality and based on the discussion above, the service provisioning process is the only service which is strongly impacted on by the GMPLS control plane, and the efficiency of GMPLS should be assessed on the basis of this service.

If so then we must take into account the frequency of the service request when calculating the cost benefits of the control plane framework, which is deeply related to the cost of newly invested capital.

#### 3.6.2.3 GMPLS-Enabled Networks' Service Provisioning Cost Versus Traditional Networks' Service Provisioning Cost

As stated previously, information and communication equipment has a relatively long useful life time. While we agree that the service provisioning process covers a major part of network service providers OPEX, the service provisioning process is not a frequent process in the current situation, thus the investment to upgrade the network to GMPLS-capability should be justified by considering the equipment's useful life time as well as the frequency of service provisioning.

Preliminary results of our survey for the IP/MPLS and the transport network suggest that on average transport service providers only receive one or even less than one request per week for a service provisioning link. This was also suggested by other scholars. Bernstein, et al [2000] stated that the service provisioning process is not a frequent process but only occurs a few times per week. And so, if we consider the case that the greatest economic gain of the GMPLS control plan comes from the reduction of human intervention in the process of network management and network control where the main focus is on service delivery, then we should include the frequency of the service provisioning process in order to provide a more accurate cost efficiency estimation.

In order to calculate the per-service provisioning cost of newly invested capital, we consider the total cost for migration to the GMPLS control capable network shown in Figure 3.3, the useful life time of the telecommunication equipment estimated by the Internal Revenue Manual [2010], and the frequency of service provisioning. Equation (6) shows how the newly invested capital cost (Cdep/y) has been calculated. A straightforward way of calculating the cost of the newly invested capital pre-service provisioning process is to divide the total cost of the equipment by its total useful life time. The resulting value shows the per-yearly depreciation cost of the newly invested capital.

$$C_{dep/Y} = \frac{total\ cost}{Useful\ life}$$

Equation (6)

For our specific purpose, in order to estimate the cost of the newly invested capital, per service provisioning (SP), we must divide Equation (6) by the average number of service provisioning requests per year, which is assumed to be 42 times per year. Equation (7) shows the per-service provisioning cost of newly invested capital.

$$C_E/SP = \frac{\frac{total\ cost}{Useful\ life}}{Avrage\ SP\ requst/year}$$

Equation (7)

Figure 3.4 shows the cost of newly invested capital per service provisioning process for networks with 10, 20, 30 and 40 nodes, each assuming to have 20%, 30%, 40% and 50% of replaced hardware. Equation (7) is applied to calculate the per-service provisioning cost of the newly invested capital.

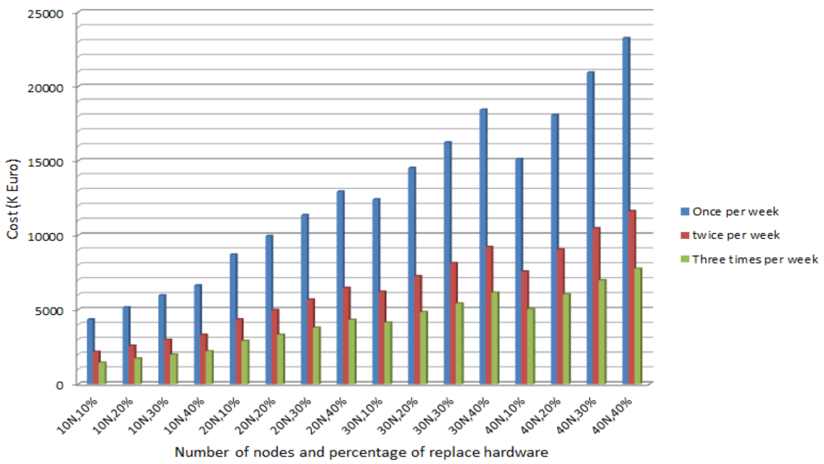



Figure 3.4 Depreciation cost of newly invested capital
per-service provisioning process

Based on the result of our calculation, which is shown in Figure 3.4, the cost of newly invested capital per service provisioning varies between 1450 and 23268 (K Euros) depending on the number of nodes in the network, the percentage of replaced hardware and the frequency of service provisioning. To present a better picture, we consider the average frequency of service provisioning in the range of 1 to 3 times per week, while three times per week is an extreme assumption. The results of our calculation show that even for an extreme assumption like a request for the service provisioning three times per week, the depreciation cost of the newly invested capital is huge. This means that if we consider the cost of newly invested capital when comparing the OPEXs of GMPLS enabled networks with traditional networks the result will definitely be different than the findings of Chahine [2004], Pasqualini et al. [2005] and Kirstadter et al. [2006].

#### 3.6.2.4 Traditional Networks' Service Provisioning Cost

In order to estimate the cost–benefits of the GMPLS control plane compared with the traditional one, in this section we provide cost estimation for the service provisioning process in the traditional network.

As also mentioned by Chahine [2004], the service provisioning process in traditional networks involves sales, administration, project management and network operation center departments. As the process is manual, it starts from the sales department, followed by the SLA setup in the administration department, which is then sent to the project management team.

The project management department creates work packages for planning department, network operations centers, and testing and delivery and sends the work packages to the related departments. The planning department then starts the path computation process and the path selection, which is followed by equipment setup and the network operations center with its associated tests. When the path test has been completed, NOC inform administration department about the successful test. Administration department then send the service delivery notification to the requester.

In order to estimate the service provisioning cost in traditional networks, we identified the activities that need to be executed in each department and summed up the required time for the successful execution of activities in each department. Then we added the cost for each activity based on the employee rank and their wages. The wages and the employee ranks were based on the classification of the Telecommunication Service Award [2010].

Table 3.3 shows the involved in the process of service provisioning employees' ranks, their wages, work hours required to execute activities, the activities and the departments involved in the process. As the GMPLS technology cost is derived in Euros, we changed the traditional SP cost to Euros with the assumption that 1USD = 0.7581€.

Table3.3. Traditional networks employee ranks, wages and work hours

| **Departments involved** | **Employee rank** | **Activities** | **Duration (hours)** | **Total Duration (hours)** | **wage Per-hour USD** | **Total cost** |
|---|---|---|---|---|---|---|
| Sales | Customer contact office L1 | Contact handling | 1 | 3 | 16 | 48 |
| | | Administration | 1 | | | |
| | | Service delivery notification | 0.5 | | | |
| | | Forward to system administration | 0.5 | | | |
| Administration | Clerical and administration emp.L3 | Request registration | 1 | 10 | 16.6 | 166 |
| | | Policy based decision | 7 | | | |
| | | Forward to system engineer | 2 | | | |
| System Engineer | Telecom associate | Create work packages for: | | 6 | 22 | 132 |
| | | • Planning | 2 | | | |
| | | • NOC | 2 | | | |
| | | • test and delivery | 2 | | | |
| Planning | Advanced telecom technician | Path computation related activities | | 39 | 19 | 741 |
| | | Topology analysis | 2 | | | |
| | | Traffic matrix analysis | 7 | | | |
| | | QoS/priorities, requirement analyses | 7 | | | |
| | | Constraint related studies | 2 | | | |
| | | Path computation and path selection | 21 | | | |
| NOC | Telecom trainee | Provisioning activity | 4 | 8 | 16 | 128 |
| | | Test and delivery | 4 | | | |
| Total | | | | 66 | | 1215 |

### 3.6.2.5 GMPLS-Enabled Network Service Provisioning Cost Compared to Traditional Systems

After adding the employees' wages to the hours of work they need to execute the required activities, we include 10% in overhead costs to capture the cost related to the non-human capital cost of service provisioning. The traditional network service provisioning process cost is calculated based on the equation shown below

$$TSP_c = \left\{ \sum_{i=1}^{k} D_{Ai} * C_{Ai} \right\} + X$$

Equation (8)

In Equation (8), $D_{Ai}$ represents the duration of time (in hours) that a specific activity (ί) needs in order to successfully accomplish, $C_{Ai}$ represents the (ί) activity's hourly cost, and X, represents the percentage of overhead cost (non-human activity related cost) required to perform service provisioning in a traditional network. Figure 3.5 shows the per service provisioning technology cost for networks with 10 nodes with 20%, 30%, 40%, and 50% replaced hardware, compared to the traditional service provisioning cost for networks with the overhead costs of 2 to 10%.

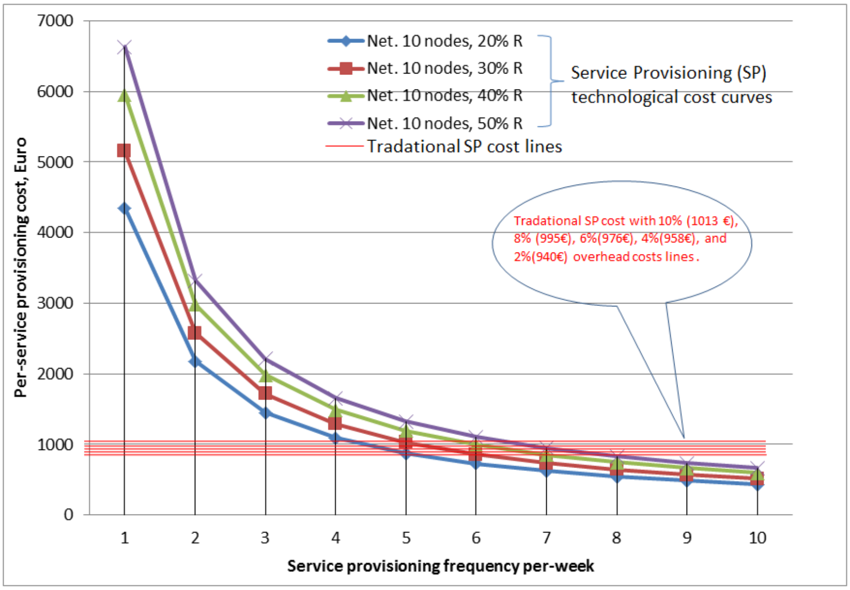



Figure 3.5 GMPLS service provisioning cost versus
tradational system service provisioning cost

As can be seen from the figure above the GMPLS control plane per-service provisioning cost reduces as the number of service provisioning requests increases. The figure also provides an estimated cost of service provisioning in a traditional network. Based on our calculations and as shown in Figure 3.5, the per service provisioning technology cost is higher than the traditional system (with a 10% overhead cost) for networks with 10 nodes with 50%, 40% and 30% of replaced hardware, if the frequency of service provisioning is less than 5 times per week. But for all types of network shown in the figure, the technology cost for service provisioning is less than the traditional systems when the request for the service provisioning is more than 5 to 8 times per week (depending on the traditional network SP overhead cost). This suggests that the GMPLS control plan deployment is viable if the network operators serve more than 5 to 8 services per week.

Figure 3.5 can be used as a decision support for the network operators to decide when it is economically efficient to deploy the control plane framework.

Furthermore, they can move the traditional service provisioning cost line according to their real service provisioning cost, and then decide when to invest or migrate to the GMPLS enabled network.

Figure 3.6 provides the same decision support opportunity for network operators with a larger network. This also suggest that as the network nodes increase the migration cost to the GMPLS enabled network will increase, and consequently the technology cost for the service provisioning process is higher for all three networks which have more than 10 nodes, if the network has a 5% overhead cost for the traditional SP process. Based on our estimation the technology cost for service provisioning in a network with 20 nodes approaches the traditional network if it has more than seven requests for service provisioning per week.

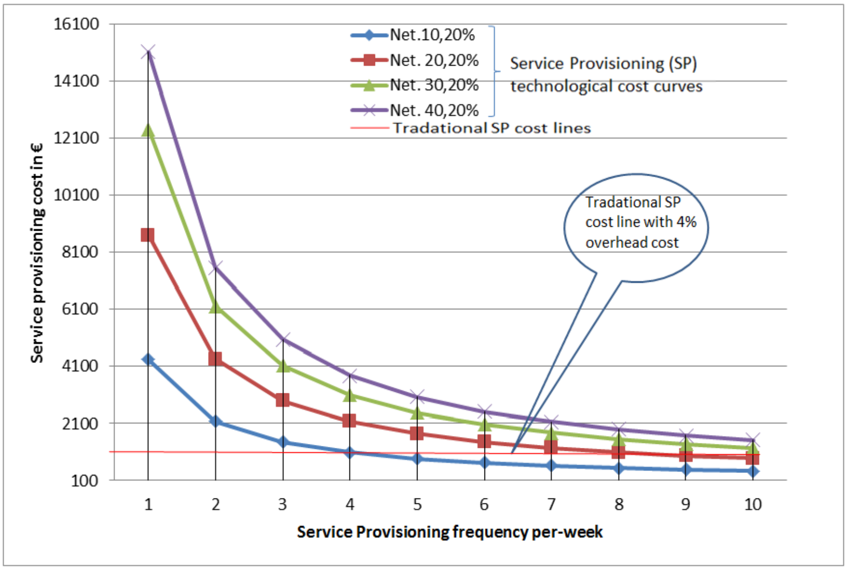



Figure 3.6 GMPLS enabled network service provisioning cost
versus tradational system for the network with 10, 20, 30 and 40 nodes each

In general, our GMPLS cost-benefit estimation suggests that, if the GMPLS control plane advantages for network operators is limited to the functions related to service provisioning and service cease, then it is deployment is economically justified when there are enough applications for on-demand provisioning.

## 3.7 Summary of Chapter 3

Our investigation results suggest that the low interest from network operators regarding control plane frameworks deployment, and the activation of all its functions for those operators who have already migrated their network to the control plane enabled network, has its root in technical and economic factors.

The technical challenges identified are the complicated operation and maintenance, the requirement for highly granular policies, the GMPLS inability to cope with unexpected incidents, and the difficulty to change the process.

The economic challenges are the requirement to replace or upgrade all existing network devices to GMPLS capable ones, the high cost of new technology, and of course the cost of hardware subject to be replaced while still useful and not having completed its depreciation period.

Our investigations also suggest that the control plane deployment cost increases as the percentage of network hardware that is not eligible to be upgraded increases. The per node deployment cost of GMPLS technology decreases as the number nodes in the network increases, as well it decreasing as the percentage of replaced hardware increases.

Apart from the above-mentioned, the GMPLS cost–benefits evaluation in terms of service provisioning suggests that we must take into account the cost of newly invested capital to assess the cost efficiency of the control plane framework for a network which is up and running. Furthermore, this also suggests that the claims of previous authors regarding the control plane enabled network OPEX reduction by 50% are controversial and need to be re-checked.

Our investigation results can be used as a decision support tool for network operators to decide when it is economically viable to migrate to the GMPLS control based network. More specifically, Figures 3.5 and 3.6 provide such an opportunity. A network operator can apply their real service provisioning cost line to decide whether or not to deploy the GMPLS control plane.

It is worth mentioning here that we believe that in the future the Internet will be built over the frameworks proposed by IETF and ITU-T. The reason behind our optimism, even after our findings, is the current trend for bandwidth on-demand services, as well as the step by step deployment of GMPLS capable equipment.

To the best of our knowledge, while there are currently not enough bandwidth on-demand services in exist, the future of the Internet will be evidence of many applications with an on-demand requirement. Furthermore, the yearly network upgrading plan, as well as the added future of new equipment, gives us optimism that in the long run the deployment of the GMPLS control plan will not be as expensive as today. Furthermore, the efforts of standardization bodies as well as research support organizations and individual researchers are directed towards addressing the challenges of the control plane framework, which offers hope that in the future ASON/GMPLS will be the technology of choice.

In view of the fact that network operators are always looking for ways to reduce the operational costs of networks, introduce flexibility, and increase network utilization, the proposed frameworks are not found to be a desirable solution. Therefore there is a need for an easy to deploy and cost effective solution to the problem for today and the near future.

# Chapter 4. Proposed Architecture for a Mediator Between the IP Networks and Transport Networks

## 4.1 Introduction

As discussed previously, the current isolation of the IP and transport layers are the main reason for the high operational cost of transport providers and the lack of opportunity to allow new services over the network.

In current practices, the IP and transport layer network management system needs human operator communication to send or receive information from each other. Figure 4.1 clearly describes the current practices in communication between the two layer NMS.

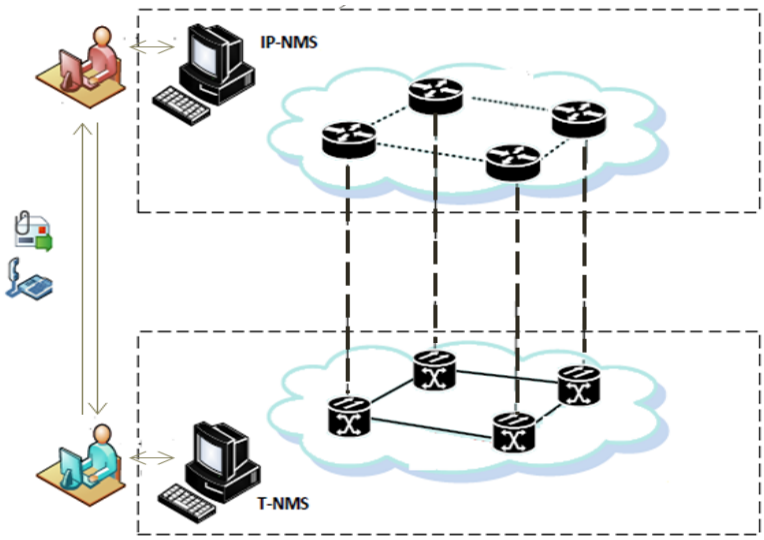



Figure 4.1 IP and the transport layers NMS intraction current situation

As stated before, in order to address the network management and network control challenges faced by the IP and transport networks, IEFT and ITU-T have introduced a control plane framework proposing the integration of two layer network management systems. Figure 4.2 describes the standardization organizations' approaches.

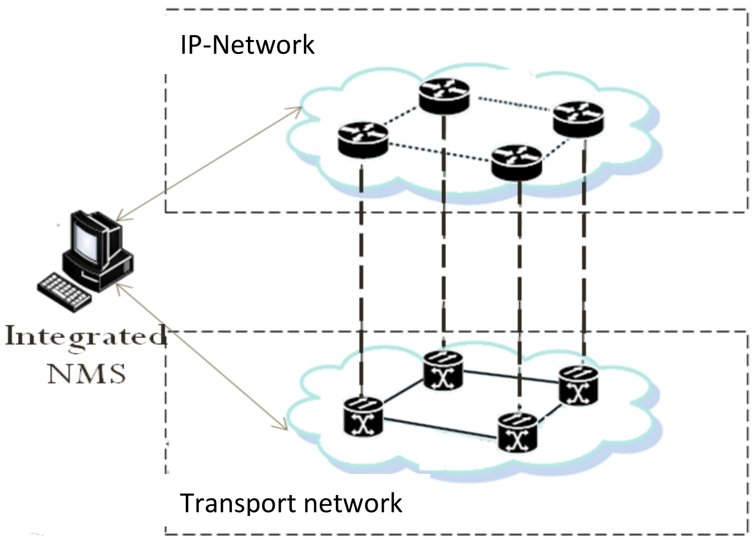



Figure 4.2 Netowrk mangement system intigration approches

While standardized, the integration approach is not found to be a desirable solution, either due to the traditional separation between the two parts of the organization or due to the techno-economic challenges discussed before.

The mediator model concept is developed on the basis of interoperability challenges between the IP and transport layers. The interoperability issues between the layer and the domain in the Internet is the main barrier in the way of coordinated network management and network control. The second important issue is a lack of trust, which restricts the network information flow between the network operators for access by others in order to coordinate the required function.

The main objective of this module is to overcome the above-mentioned barriers, so as to allow coordination of network management tasks as well as to allow new services to be run over the network. In this chapter we introduce the proposed mediator model architecture and the possible ways of its integration into the current Internet ecosystem.

## 4.2 Coordination-Based Approach

As stated previously, the shortcomings of today's multi-layer, multi-domain network environment are mainly consequences of the static nature of legacy transport networks and their manual operation. Additional factors contributing to low interoperability are differences in the communication languages, the multi-standard technology usage and the differences in the switching technologies of each layer. These shortcomings have limited coordination opportunities between the two layers and have led to the isolation of the IP layer and the transport layer and, consequently, to the high cost of network control and management. As a result, the current multi-layer Internet suffers, from manual and error prone link/service provisioning, long provisioning times, inefficient resource utilization, little interoperability, complex network management, low reliability, and low scalability problems [Clavena, 2002].

We believe that by directly addressing the barriers of coordination between the layers we will be able to resolve most of today's network provider problems and enable system automation of network management.

To overcome the barrier of multi-vender technology incompatibility, it is better to rely on the network management systems of each layer than converging two heterogeneous network layer technologies. Our approach is to deploy a mediator between the IP layer and the transport layer. It provides the necessary functionalities to support system automation and to reduce the operational cost of networks. For example, the automation should include link/service provisioning, multi-layer fault management, and IP traffic offloading possibilities. As shown in figure 4.3, a Mediator Model (MM) between the IP-NMS and the transport NMS can facilitate such a coordination to allow automatic interaction of two system replacing the operator to operator communication to the system to system communication.

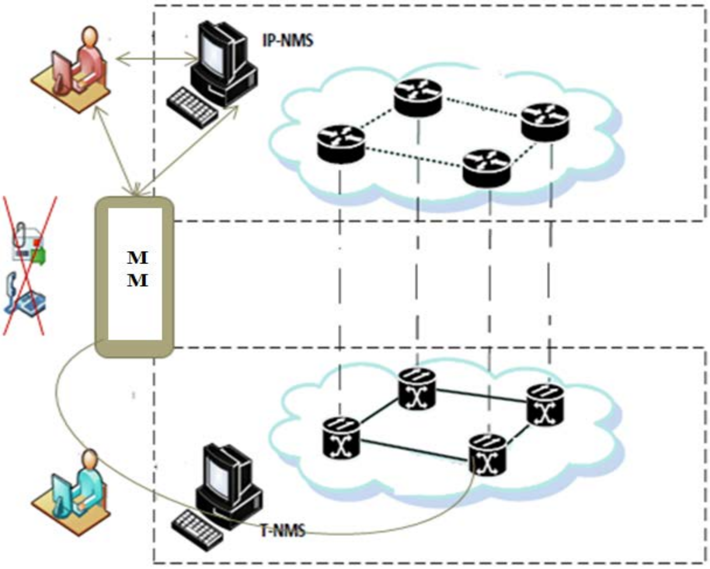



Figure 4.3 Coordination based approach

Considering that there are many different network technologies with different levels of control and management (e.g. SDH/SONET, Optical Transport Network (OTN), WDM, control plane enabled WDM and DWDM) in existence in today's transport layer, we also need to anticipate coordination among networks with different capabilities.

## 4.3 Mediator Model Concept (ONE Adapter)

For the first time the mediator module concept has been developed within the ONE project [ONE, 2011], facilitating automatic communication between the IP and transport network layers.

The main goal of the mediator called the "ONE Adapter" is to allow coordination of tasks between the network management systems of the two layers, to achieve better resource utilization, time and cost reduction in terms of IP/MPLS link or service provisioning, automatic multi-layer fault management, support for IP traffic offloading, and automatic recovery from link or node failures.

The ONE model architecture consists of two types of module: the ONE core modules and the ONE auxiliary module (Figure 4.4). According to ONE, D2.2 [2012], the core modules comprise the base functionality that needs to be present to allow smooth interaction, coordination and communication between the two layers. The auxiliary modules make the architecture adaptable to any network environment.

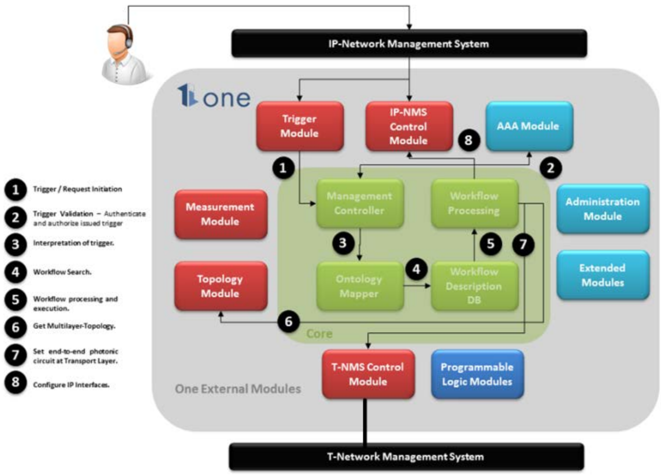



Figure 4.4 the ONE Adapter architecture design.
Source: ONE project (With the permission of ONE consortium)

The ONE core modules consist of four sub-modules, specifically the management controller (MC), the ontology mapper (OM), the workflow processor (WFP) and the workflow database (WFD). The ONE auxiliary module are the Trigger module, the IP-NMS , T-NMS, the measurement module (MM), the configuration logic module (CL), the path computation client (PCC), and the ONE administration module (ONEA).

The ONE consortium proposed management adapter is designed with the assumption that the module will be integrated into the IP layer, while having access to the data layer of the transport service provider network for making changes according to the service demanded. Furthermore, the ONE project assumes that an enterprise path computation provider exists in the market which provides the path computation function that will be requested by the ONE adapter. Similarly, the ONE project approach limits the functionality of the mediator model to a single domain.

Before discussing the extended mediator module architecture developed under this dissertation, I would like to raise my concerns regarding the ONE project approach. Firstly, the ONE consortium has designed the management adapter specifically to integrate it between the single IP network and its associated transport provider. In this way control over the transport layer's resources will partially move to the IP layer, which may lead to the destabilization of the transport network if the IP layer changes the transport layer resource as they wish. In current practice, where there is a separation between the IP and transport side of the company [Narayanaswamy, 2011], it is not reasonable to expect that the transport layer will allow the IP layer to access and manage transport layer devices.

Secondly, to the best of our knowledge, there is currently no enterprise path computation provider existing in the market. If this is the case then the ONE Adapter services rely on third party services that are currently not in existence.

Finally, the ONE consortium developed the mediator module for a single domain. This means that if a transport provider peer has (for instance) 10 IP network providers then every IP network must integrate one module of the management adapter, which in general will cost the company 10 times the cost of deploying one multi-input-output mediator module in the transport layer.

### 4.3.1 Extended Mediator Model Architecture

As stated in our objective, we propose an easy to deploy multi-input, multi-output adapter to allow it not only to be useful in a single domain but to be accessed and used by multiple domains in the Internet. In our approach we consider the sensitivity of boundary separation between the layer and the domain, as well as the traditional schism between the IP and transport sections of the company.

Furthermore, our proposed model executes the major management task, namely the path computation, which makes the mediator a path computation provider instead of path computation client. Figure 4.5 shows the proposed mediator model between the different layers and the domain in the Internet.

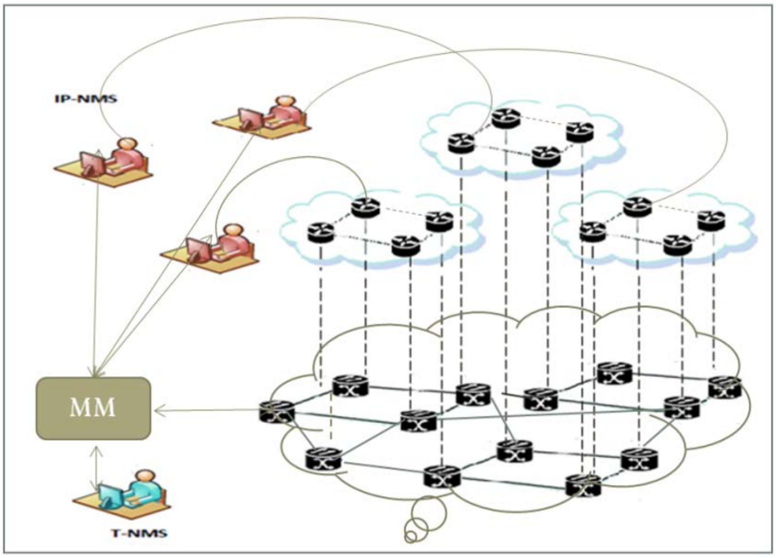



Figure 4.5 Multi-input, Multi-Output Mediator Model interaction with different in the layer and the domain network

The MM architecture consists of two types of module: core modules and auxiliary modules (Figure 4.6). The core modules comprise the base functionality that needs to be present to allow smooth interaction, coordination and communication between the two layers. The auxiliary modules execute supportive tasks such as path computation and overall mediator module management. These modules can easily be added or dropped. Therefore, the mediator module administrator can adapt the architecture in accordance to the network policy and capabilities of the connected networks without changing the core modules.

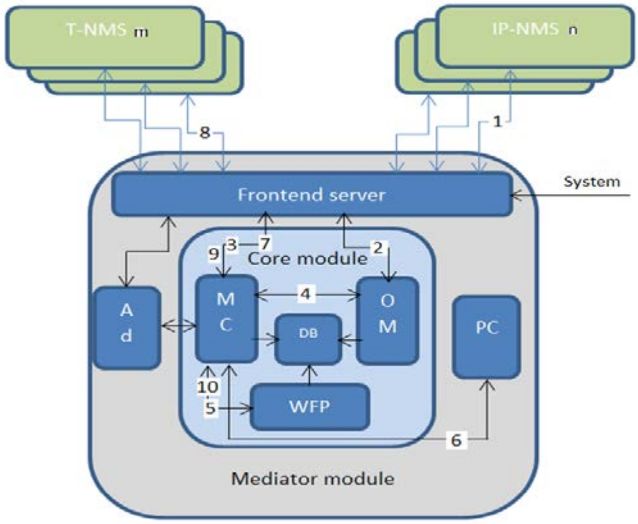



Figure 4.6 Proposed MM, mediator module architecture and its interfaces

The MC is responsible for managing all the communication between the core modules, as well as their interactions with the outside world. It is also responsible for keeping stat of the activities, policy enforcement, and workflow execution approval. The OM is responsible for translating trigger information, for information extraction, and for translating any request that passes to or from any of the core or auxiliary modules to the outside world. The WFP deals with the workflow execution and workflow performance control. The DB archives workflows, policies and priorities and the status report.

The frontend server (FEM) module, which is one of the auxiliary modules, combines sub-modules such as the authentication and authorization (AA) module, the trigger module, the IP-NMS service module, and the T-NMS service module (Figure 4.7). It receives triggers from the IP network management system (IP-NMS) as well as from the system, and SNMP traps or signals. The FEM module can be considered an interface module between the IP-NMS and the transport NMS, since all information exchange will be handled by the IP-NMS service module and the T-

NMS service module. The PC is responsible for computing the path between the source and the destination nodes in the network and reporting the suitable path found in the network. Finally, the Ad supports the mediator administrator in loading new workflow, providing maintenance services for different modules, as well as adding or dropping auxiliary modules.

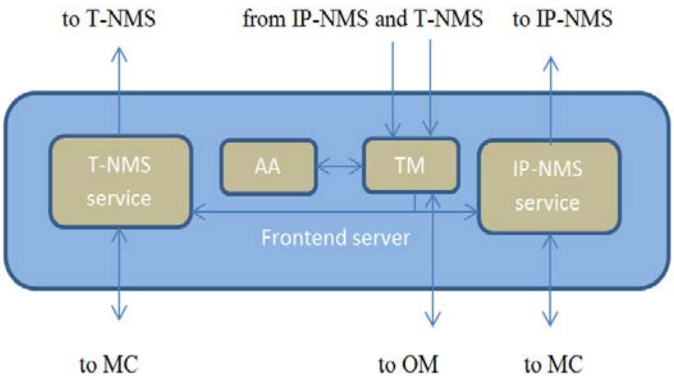



Figure 4.7 Frontend server architecture and interfaces

### 4.3.2 Mediator Module Service Area

Since the mediator module is not only designed to work in a single domain environment (i.e. the IP network belongs to the same administrative domain as the transport network) but also in an environment in which the IP network does not belong to the same administrative domain as the underlying transport network, the mediator module provides different levels of information exchange for coordinated actions between multiple IP/MPLS networks and their corresponding transport providers. The level of critical information exchange depends on whether the information is kept in the same administrative domain.

Furthermore, the mediator needs to be cost effective, which can be achieved by providing the service to a large number of customers as a service. It implies that the mediator module should be capable of providing simultaneous services to different IP/MPLS providers and their corresponding transport providers.

Therefore, the location of the mediator is an important issue that needs to be considered. In the case that the IP network and the transport networks work under different administrative domains, the mediator needs to be located in a neutral location, acceptable and accessible to many IP/MPLS network providers and their corresponding transport network provider. Consequently, the Internet exchange point (IXP), where IP/MPLS providers can build cost-effective service level agreements, is an appropriate solution. IXP are trusted by network providers to co-locate routers and switches, which contain routing information.

In the same way, the mediator needs an environment that is trusted by the network providers. Only then will the exchange of information between the network layers happen. Therefore, we expect the location of the mediator module at the IXP node to be acceptable to the IP/MPLS network providers and the transport network providers. The mediator will provide services to m IP/MPLS networks and to their corresponding n transport network providers.

### 4.3.3 Mediator Module (MM) Interconnection

Figure 4.8 shows an example of the interconnection of the mediator module (MM) with IP/MPLS networks and transport networks. The mediator module is co-located in a Layer-3 IXP. The IXP node interconnects m IP/MPLS networks via the IXP router. The IXP provides the opportunity to IP/MPLS networks to establish peering agreements between them. The mediator is connected to the IXP router in order to allow IP/MPLS providers to access the mediator services. In addition to this, the mediator is connected to the edge routers of the transport network providers. For this, the transport network providers need to extend their connection to the IXP and connect their edge routers to the MM. In our example, the mediator is a separate device connected to the IXP main router as shown in Figure 4.8.

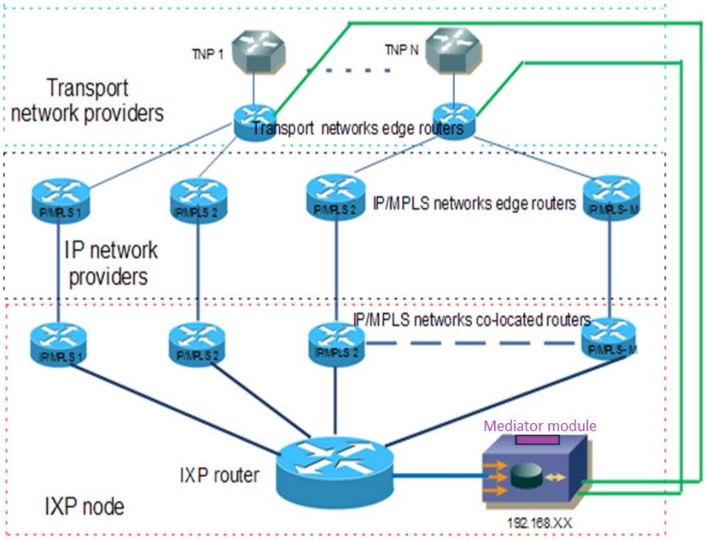



Figure 4.8 IXP node host mediator module

For clarification, we describe the interconnection of the IP-NMS and the interconnection of the T-NMS to the MM in detail. Figure 4.8 shows one of the m IP/MPLS networks which is connected to the IXP and via IXP router connected to the mediator module. The figure also only shows one transport provider that serves the above-mentioned IP/MPLS network. We assumed that each layer has a specific management system, as also shown in Figure 4.9 the MM communicates with the IP-NMS via the IXP node router (dashed line), while it interacts with the transport network management system via the transport network edge router.

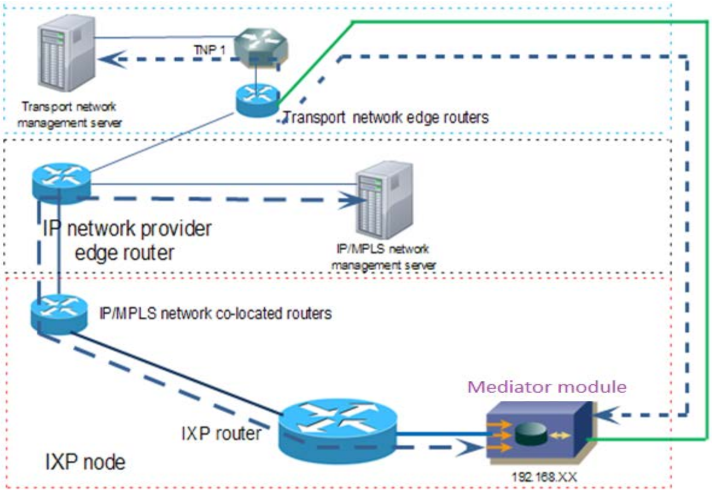



Figure 4.9 MM interconnection with IP/MPLS network management system and the T-NMS

There are two reasons why the mediator module does not communicate with the transport layer via the IXP over the IP/MPLS network. Firstly, in order to be as general as possible, we assume that the IXP only provides a peering service. Secondly, in order to make sure that the information of one layer is not leaked to another layer, the MM should not communicate with the transport network T-NMS through the IP/MPLS network.

### 4.3.4 Virtual Private Network Provisioning Use Case

In this section we describe how the automatic interaction between the IP-NMS and the T-NMS will take place via the mediator module if the IP layer requests a VPN for provision between the two routers. The use case is designed based on the following assumptions: 1) the IP-NMS does not have the capability to automatically configure the router port; 2) the IP-NMS provides the MM with the QoS constraints information, which is required for the provisioning process. The QoS constraint information comprises the path information, the required bandwidth, the IP addresses of both routers, and the port numbers; 3) the transport network does not have the capability of automatically performing path computation; 4) the IP network and the transport network already agreed to use the MM service; 5) the IP network allows the MM to configure the IP router ports; 6) both networks will provide the necessary information for path computation; 7) both layers negotiate the SLA immediately and can perform accounting; 8) for simplicity of the workflow description, we consider a case where the trigger information is valid and includes all necessary information.

The sequence diagram presented in Figure 4.10 shows the process of provisioning a VPN between router X and Y, which has been requested by the IP/MPLS network management.

In detail, we presume that, after analyzing the requirements, the IP network operator j issues a trigger to the MM containing all necessary information for provisioning a VPN between routers X and Y via transport network i. The trigger is first received by the FEM module, specifically by the trigger listeners which are located in the trigger module (TM) and send the received information to the OM for semantic interpretation. After which, the TM communicates with the AA module, where it performs security measures such as checking initiator rights for specific trigger initiation and sender network rights for requesting a service. If the trigger is found to be valid, then the FEM module passes the request to the MC. But if the request has not been found to be valid, the FEM will send a termination message to the IP-NMS via the IP-NMS service. The MC stores the header information of the trigger, which includes the network ID number, the initiator ID, the corresponding transport network ID, and an indication about the IP and transport layers' relationship (e.g. belonging to the same domain or to different domains).

At this point the trigger has been found to be valid. Therefore a specific ID number is added to any message within the MM, in order to differentiate this process from any other. Afterwards, the MC sends the trigger to the OM, where the trigger information will be translated into a language that is understandable within the mediator modules. The OM sends the translated version of the trigger back to the MC. Afterwards, the MC stores all the information into the database and acquires the workflow ID from the WFD for the service requested (i.e. VPN service provisioning) and sends a request with the workflow ID to the WFP for executing the corresponding workflow. The workflow ID specifies the workflow, which is specific to the relationship of both networks involved and of the service requested.

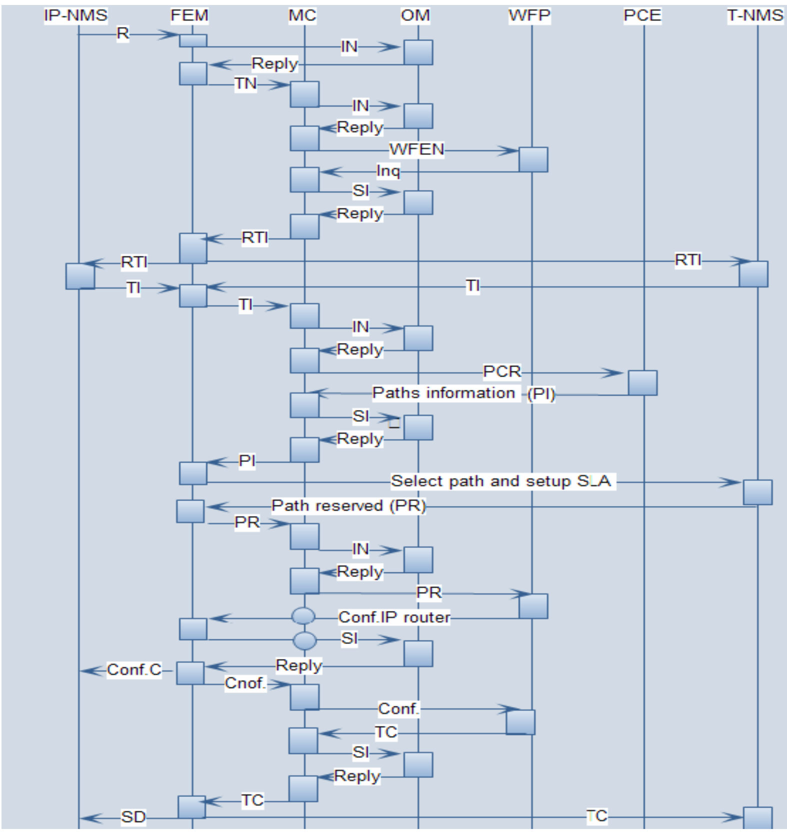



Figure 4.10 VPN provisioning workflow sequence diagram

The WFP executes the first step of the workflow which has already been saved in the workflow repository. Subsequently, the WFP sends a request to both network management systems, the IP-NMS and the T-NMS, demanding the network topology information and the traffic matrix via MC, OM and FEM. Information about the network's topology and the traffic matrix is sent back to the MM via the IP-NMS and T-NMS service module, and is passed to the OM through the MC. Following the translation within the OM, the OM sends the information via the MC to the WFP. Once a reply for step 1 of the workflow has been received, the WFP sends all the information for the path computation to the PC through the MC and OM, where the request is translated into a language that understandable by the PCE, and is recorded in the database of the MC. The PCE sends the path computation result to the MC.

In order for the transport service provider to select a path among the paths found, as well as to setup the SLA, the MC sends the path computation result to the T-NMS via the OM and T-NMS service. Once T-NMS has received the path computation notice it reserves the proper path and starts SLA negotiation. The T-NMS acknowledges the result of the path reservation and the SLA negotiation with the MM. In view of the information received from the T-NMS, the WFP either sends a command via the SNMP interface to perform router configuration in the IP layer or to terminate the process in the case a SLA not being negotiated. Assuming that the SLA is negotiated and the path has been reserved, the configuration logic module located in the IP-NMS service module configures the IP layer routers and sends an acknowledgement back to the WFP.

As the final step, the WFP sends a notice to the T-NMS to test and connect the path and a notice to the IP-NMS that the service has been delivered. If, however, the path computation could not find a path, the FEM sends information to the IP-NMS and terminates. At the end of each workflow, the MC erases all unnecessary information and saves the information (e.g. topology information and traffic matrix) required for future services.

## 4.4 Summary of Chapter 4

The mediator module (MM) introduced in this chapter aims to ease the issue of shortcomings of the IP and transport layers in the Internet by allowing the coordination and automatic execution of management tasks between the two layer management systems.

Unlike the approach of the ONE project, the architecture designed allows the MM to be useful for multi-layer, multi-domain environments in the Internet ecosystem. Furthermore, the proposed architecture and its integration point let the MM offer services for “n” number of IP/MPLS networks and their associated transport providers.

We expect that the mediator services will be cost-effective and acceptable for both the IP layer and the transport layer as we locate the mediator in an IXP, which can be considered a trusted entity between the IP/MPLS network and the transport network. Additionally, we designed the MM such that it can serve multiple IP/MPLS networks and multiple transport networks simultaneously. Therefore, the MM design fulfills current and future network operators’ demand. It is easy-to-deploy, cost-effective, acceptable by network providers, and accessible by both layers.

# Chapter 5. Mediator Model Impacts on the Value Creation Activities of Transport Service Providers

This chapter presents the changes in the value creation model of network service providers in the Internet ecosystem incurred by ONE Adapter technology deployment. The reference model introduced by Pussttchi and Hufenbach [2011] analyzes the impact of new technology in terms of the players, their means of interaction and new services.

## 5.1 Introduction

The last three decade witnessed drastic change in telecommunication service providers' (TSP) business models. Previously there had been fewer services offered by TSPs, among which the voice service was the main source of revenue. While the TSPs' business models remained unchanged for many years, the birth of the Internet had a huge impact on it.

The introduction of IP-based applications, which became part of human life, has increased the role of data communication, and consequently network service providers were flooded by bandwidth demands. SDH/SONET-based transport networks with their static nature and manually designed operation were found not to be ready to fulfill the increasing demand for bandwidth.

To overcome the problem, the integration of IP/MPLS and transport layer network management systems was proposed and standardized by IETF and ITU-T. Whilst the GMPLS and the AOSN control plane frameworks introduced by the IETF and the ITU-T address the management issues between the two layers, the coordination of management functions remains unsolved.

This dissertation proposes a mediator model to address these shortcomings of network management and network control, while facilitating automatic interaction and the coordination of management tasks between the two layers.

Since the introduction of the mediator model will lead to changes in the current business models, the aim of this chapter is to capture and analyze these changes.

A value creation model for network service providers is presented, which is developed based on the reference model introduced by Pousttchi and Hufenbach [2011]. In particular, the impact of the mediator model is investigated and analyzed. The data gathered worldwide from 15 leading telecommunication operators is used to define the network service provider's roles, relationships and the services they provide to each other.

## 5.2 Literature Review

The birth of the Internet forced telecommunication providers to adapt to the new environment where distance was dead and bandwidth was moving towards infinity, where you need to charge for network connections, for privacy, advertising, and quality of service and for billing [Tanaka, 2000]. Today's TSPs have a complex business structure which is not possible to combine into a single business model. Rappa defines ten basic categories of business in the telecom industry, which include brokerage, advertising, infomediary, merchant, manufacturer, affiliate, community, subscription and utility [Rappa, 2011]. Kwiatkowski [2009] states that depending on how the carrier providers react to the changing market environment, two different business models are foreseen for mobile operators. These are customer-centric and the telco-centric models.

As also mentioned by Valitalo and Kwiatkowski [2009], the telecom sector business models are changing, not only because of the huge number of partners in the telecom sector but also due to the age of the current BM. A new business model for IPTV is discussed by Luzar [2009], who provides an insight into the revenue sources of IPTV virtual network operators and into who can become an IPTV provider. Kapusta [2009] argues that convergences in network and service management as well as the TSPs diversity of services have a large impact on the network management system. The network service provider's opportunity to deliver content over the IP and backbone networks are discussed in VELOCIX [2010], where four types of business model to enhance the network service provider position are defined. These are the retailer, the wholesaler, and the broker and transporter business models.

The application service provider business model and it is implementation in the iSerise Server of IBM is discussed in IBM Red book [2011]. It is argued that anyone who use applications provided over the Internet has a relationship with the Application Service Provider. The mobile telecommunication sector's BM requirements and challenges are discussed by Ballon [2007], who argues that the revelation in the telecommunications sector is driven by innovative technologies, globalization and deregulation. The recent development in mobile technology is triggered by the generation of new business models [Ballon, 2007; Kim, Lee and Park, 2008]. Mobile and fixed telecom operators are facing new competition and challenges focusing on the new services to be provided over the traditional networks. To deal with the new situation, they have to change their business models [Alcatel Lucent, 2007].

Different methods are applied by scholars to analyze the changes arising in the telecommunication sector. Porter [1988] introduced a value chain analysis technique, where he discusses the terms value chain, value activity, primary activity support activities, activity classification, linkages, internal linkages and the vertical linkages. Five dimensions of value creation are introduced by Verna [2008]. The supplier's value proposition diversity was studied by Merkle and Loan [2004]. The authors argue that supply chain effectiveness plays a major role in any successful business. The problem for companies to improve their initial gains after the re-engineering business process is discussed by Erna [2009], who considers the practice of value network analyses and the growing adoption.

As can be seen, telecommunication sector businesses are diverse, covering providers of fixed telephones, mobile phones, broadband, content, storage, cloud storage and many more, each of which has its own sub-business model. While multiple business model discussion papers on the telecom sector can be found, there is no single paper that can be found which discusses the network service provider BM. In this dissertation we try to fill this gap by presenting the network service providers value creation model and the impact of new technologies, in terms of changes in the new means of interaction and the role of the new players in the chain.

## 5.3 Network Service Providers, their Relationships and Services

To define the network service provider business market players, their relationships and the services they provide, it is essential to understand the nature of this business and to introduce the providers of network services in the information and communication industry (ICI).

### 5.3.1 Network Service Business

The term network service describes many impressions in today's information and communication businesses. It is used by scholars' to represent the services hosted by a server to provide shared resources to client computers, such as authentication or printing services. It also used to represent the connectivity services provided by telecommunication networks to other players in the ICI. Hereafter, by the term network service provider (NSP) we mean the connectivity service providers, and our focus will be on the connectivity services currently provided by telecommunication operators to IP/MPLS networks.

As stated before, the advancements over the last three decades in the ICI have led to the creation of new businesses that could not be managed by the traditional telecommunication networks. Computer networks and mobile networks are among many other businesses developed on the basis of telecommunication technology. The majority of ICI businesses that need connectivity services to run their services use the worldwide dispersed telecommunication network to interconnect with other networks in order to exchange information. Network services (connectivity services) can be considered one out of several areas of new businesses that have emerged in the telecommunication industry. The main goal of this chapter is to analyze the impacts of the mediator model (MM) on the value chain of network service provider businesses. Furthermore, based on the fact that the MM is designed to coordinate network management functions between the IP/MPLS and the transport layer in the Internet ecosystem, we will study Internet ecosystems in order to define the NSP business players, their roles and relationships.

### 5.3.2 Internet Ecosystem Market Players

The Internet ecosystem, which consists of countless Local Area Networks (LAN), Metropolitan Area Networks (MAN) and Wide Area Networks (WAN), mostly rely on the telecommunication network for connectivity. For the purpose of our study and to identify the stakeholders in the Internet ecosystem, we surveyed existing works on business models in the ICT industry with a special focus on communication networks. Altmann, Ion and Bany [2007] and Altmann and Constantiou [2004] classified the stakeholders in the Internet ecosystem. They identified the main players, which include users, commercial Internet Service Providers (ISPs), private sector network providers, governments, intellectual property rights holders, and providers of content and higher level services. As the Internet permanently changes its infrastructure and operates under different policies, the number of stakeholders also increases beyond the simple structure of this Internet ecosystem.

Ecosys' investigation resulted in a reference model for the telecommunication industry. It specified the stakeholders, their roles, and relationships [ECOSYS, 2005]. Ecosys proposed a division of the telecommunication network stakeholders into four groups: a transmission network operator which operates fiber optic networks, a core network operator which manages the high-capacity core of the telecommunication network, an access network operator which oversees the last mile, from the core to the end users, and the service operator who offers value-added services on top of the services from the former three providers.

Despite this sophistication, Ecosys did not consider several types of service provider (e.g. IP/MPLS network providers or third-party suppliers) as they only intended to describe business models in the voice communication industry. Therefore, in order to define the NSP business players, their roles and relationships, we conducted a survey of 15 leading network service providers. Among all the players in the telecommunication industry 12 were identified as stockholders in the Internet ecosystem. They have been selected based on their participation in the value creation chain of the Internet ecosystem. The key players defined are; hardware vendors, content and application providers, software vendors, standardization organizations, advertisers, research support organizations, management service providers, government/regulators, IXPs, IP/MPLS network providers, transport network providers and end users. Figure 5.1 shows the stakeholders in the Internet ecosystem market.

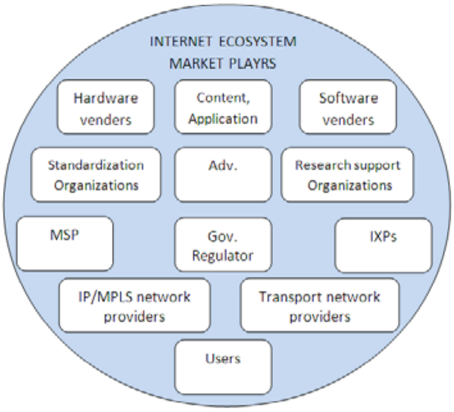



Figure 5.1 Internet ecosystem market players

#### 5.3.2.1 Existing Relationship Between Players in the Internet

Understanding the relationships between Internet ecosystem players is crucial for specifying changes in the value creation model. Specifically, we need this relationship model to determine the changes that may arise in relationships between the current stakeholders after MM deployment. For defining the relationship between the players in the ICT sector, we used the reference model that has been specified by ECOSYS [2004] and the survey we have conducted.

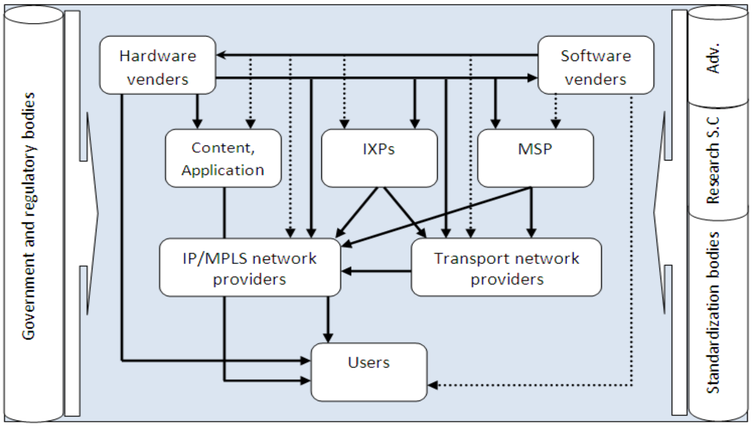



Figure 5.2 Internet ecosystem stockholders' relationship model

Figure 5.2 shows the services that each player provides to the others. Based on the fact that all required software are imbedded into hardware in today's practices, in the figure above we have shown a dotted line from the software vendors to the other players to describe the delivery of the specific application demanded. Table 5.1 below identifies the relationships and describes the services each player provides to the others in the Internet ecosystem.

The kind of service each player provides to the others is based on the results of our survey and the relationship model, as well as the information gathered to define the market players. Table 5.1 presents the findings of our survey, which is shown below.

While most of the entries in Table 5.1 are self-explanatory, some of them are explained here in more detail. The research support centers generate new ideas for executing specific tasks, available to any player. Standardization organizations provide new guidelines and standards in partnership with other stakeholders. They also foster value propositions by introducing standardized frameworks.

Table 5.1 Internet ecosystem stakeholders their roles, services and providers and consumers relationship

| Customer / Service Provider | **Hardware and software vendors** | **Government and regulators** | **Research support organizations** | **Standardization organizations** | **Advertisers** | **IXPs** | **Content & application providers** | **Management solution providers** | **Transport network providers** | **IP network providers** | **Users** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Hardware and software vendors** | Competitor | H/S | H/S | H/S and support | H/S | H/S | H/S | H/S | H/S | H/S | H/S |
| **Government and regulators** | Protection by Law and regulation (LR) | Competitor | Support | Support | Protection by LR | Protection by LR | Protection by LR | Protection by LR | Licenses, Protection by LR | Licenses, Protection by LR | Protection by LR |
| **Research support organizations** | Novel ideas, business opportunities (BO) | Novel ideas | Competitor | Novel ideas, Support | Novel ideas BO | Novel ideas BO | Novel ideas BO | Novel ideas BO | Novel ideas BO | Novel ideas BO | ========== |
| **Standardization organizations** | Business opportunities | ========== | Support | Competitor | ======== | Standardized Frameworks | Standardized Frameworks | Standardized Frameworks | Standardized Frameworks | Standardized Frameworks | Protection from monopoly |
| **Advertisers** | Awareness services | Awareness services | Awareness services | Awareness services | Competitor | Awareness services | Awareness services | Awareness services | Awareness services | Awareness services | Raises Awareness |
| **IXPs** | ========== | ========== | ========= | =========== | ======== | Competitor /Partner | ========= | ========= | Peering /transit | Peering /transit | ========== |
| **Content & application providers** | ========= | ========== | ========= | =========== | ======== | ======== | Competitor /partner | ========= | ========== | ========= | Content and application |
| **Management solution providers** | ========= | =========== | ========== | ========== | ========= | ========= | ========= | Competitor /partner | Management solutions | Management solutions | ========== |
| **Transport network providers** | Client | =========== | ========== | =========== | ========= | ========= | ========= | Client | Competitor /Partner | Transport services | ========== |
| **IP network service providers** | Client | IP services | IP services | IP services | IP services | Client | Client | Client | Client | Competitor /Partner | IP services |
| **Users** | Client | ========== | ========== | =========== | ========= | ========= | Client | ========== | ========== | Client | Competitor /Partner |

Advertisers provide awareness services to players in the value chain. Finally, the management solution providers focus on services that do not directly relate to production but rather to supporting single stakeholders (e.g. authentication, authorization, and accounting (AAA)).

## 5.4 Internet Ecosystem Players' Value Creation Model

The identity of the players, their roles and their relationships defined in the previous sections allow as determining each player's value creation activity model. The player's value creation activity model shown below is derived from the reference model introduced by Pousttchi and Hufenbach [2011]. The reference models lets us graphically and scientifically introduce the actors, their roles, their value creation activity, the value exchange and the value interfaces in the Internet ecosystem.

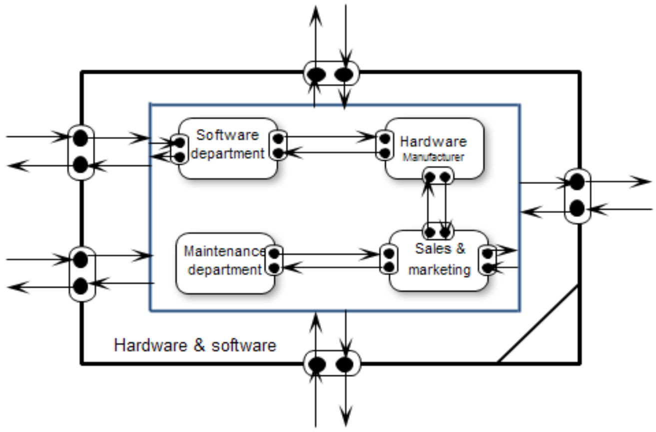



Figure.5.3 Hardware and Software players' value creation activities (VCA)

Figure 5.3 shows the hardware and software vendors' activities and the internal and external interfaces used to exchange values. We have described the hardware and software vendors in one value creation activity box. This is because the required software mostly comes with the hardware, and only in specific cases do users order extra software.

Among the four major activities specified in Figure 5.3 only two activities related departments are directly interacting with the clients. These are sales, and software departments in the case of extra software being needed. The arrows pointing out show the devices, the software and the flow of information to the users, and the arrows coming in show the flow of compensation and information.

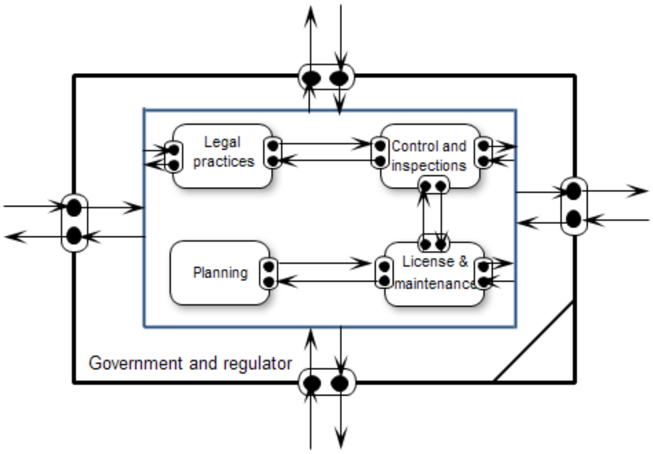



Figure.5.4 Government and Regulators VCA

Four main tasks or activities related to the information and communication industry are defined for the government and regulators. These are; legal practices such as laws and regulations, controls and inspections related to laws, regulations, and license agreements. Both organizations run planning sections as well as licensing and maintenance sections. Among the four mentioned activities, three related departments have a direct connection to the licensees, and only the planning related activities only has an internal interface with the license and maintenance section. It is worth mentioning that Figure 5.4 shows a generalization of the activities, which means that the internal and external interfaces may vary depending on the policy of the specific department. The arrows going out of the value creation box show the licenses, information about the regulations and legal aspects, and the arrows is going in show the compensation for licenses as well as the taxes and information sent to the related departments.

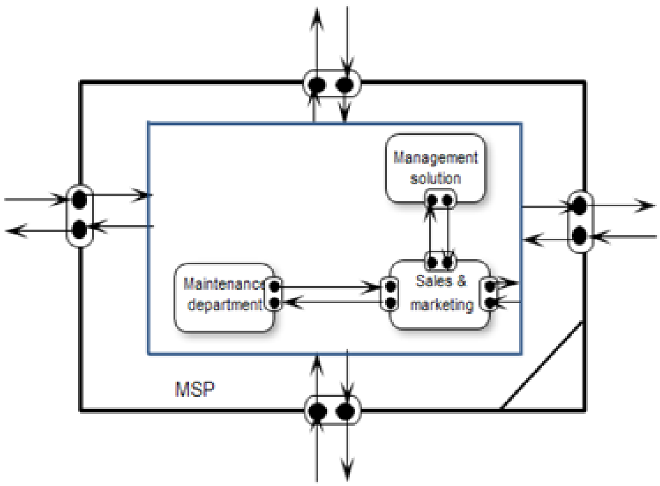



Figure 5.5 Management solution providers VCA

Figure 5.5 shows the three major functions related to the services MSP provide to the IP/MPLS and the transport service providers. The arrows going out of this value creation box show the services they provide the compensation they send to the other players for the services they receive and the information flow. The arrows going in show the compensation and the information flows. It is important to mention that we assumed that management solution providers such as AAA and PCE have the same value creation activity models.

The next value creation point is the transport service provider network. We have only specified three that they execute in relation to our business activities. Specifically, all management functions between the IP/MPLS and the transport providers could be generalized in the planning, network operation center (NOC) and the sales department.

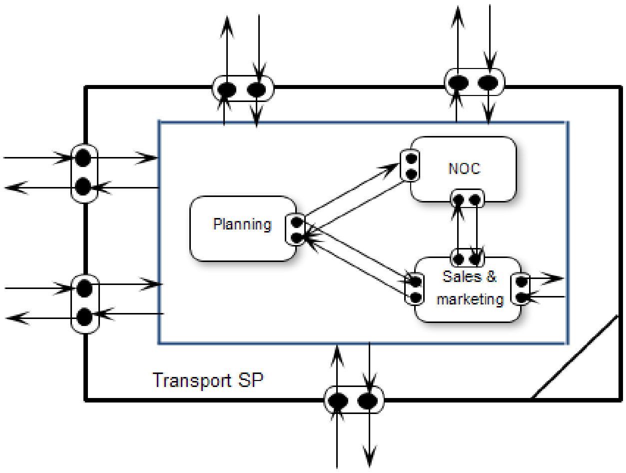



Figure 5.6 Transport service providers VCA

The arrows (in Figure 5.6) going out from this value model show the bandwidth services they provide to their customers, as well as the information flow and the compensation for the services they receive. The arrows coming in show the compensation for the connectivity services they provide to the IP/MPLS service provider and the information flow.

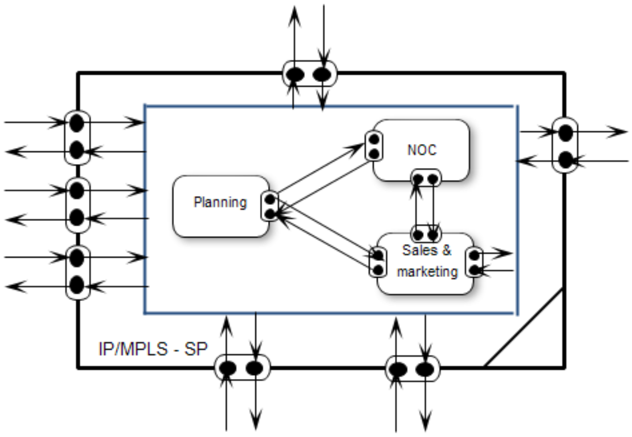



Figure 5.7 IP/MPLS service providers VCA

Similar to the transport service provider, we have defined three major activities that the IP/MPLS service provider executes (Figure 5.7). The arrows going in show the services other players in the market provide to the IP/MPLS providers or the flow of compensation for the services the IP/MPLS service provider gives to their users. The arrows going out of this model show the connectivity to the Internet for the end users as well as the compensation for the services provided by the other players to the IP/MPLS service provider.

The value creation activities of content and application providers are shown in Figure 5.8. To define the values generated by this actor we have generalized all their related activities into three major activities as shown in the figure above. The arrows going in to this model show the flow of compensation, information and the services they provide to other players in the Internet ecosystem. The arrows going out from this model show the compensation flow for the services they receive and the information flow. While it is true that users pay to the content and application providers directly, we show an abstract interface to say that the services from the content and application providers is sent to the end users via the IP/MPLS network where they pay for the connectivity services.

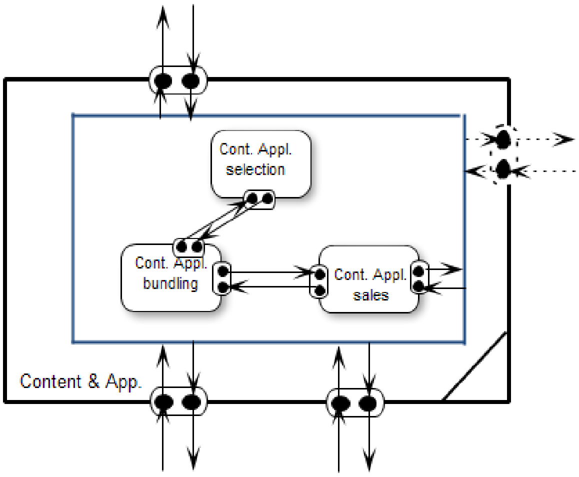



Figure 5.8 Content and Application providers' VCA

Finally the end user value creation model is described in Figure 5.9. The end users using the services provided by the hardware and software vendors, content and application providers and the services provided by their internet service provider.

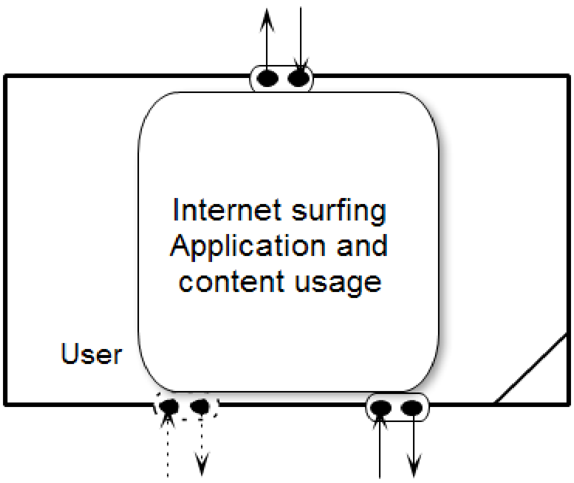



Figure.5.9 End users value creation activities

In the Internet ecosystem each value creation point interfaces with their direct value receivers, and each compensates for the services received from the others. Figure 5.10 shows the value creation model for the Internet ecosystem.

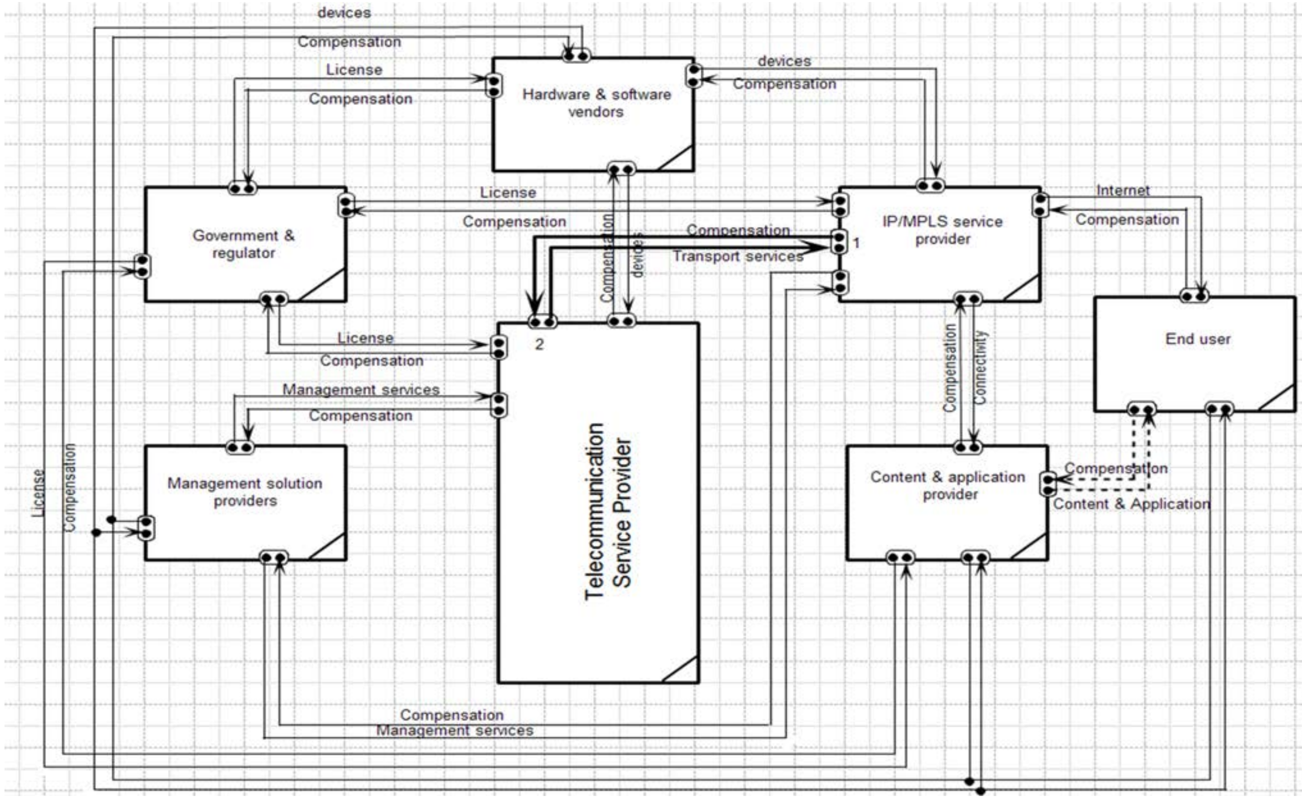



Figure 5.10 Value creation model for the Internet ecosystem

The Internet ecosystem value creation model is derived on the assumptions that; firstly, TSP is providing connectivity services to the IP/MPLS networks. Secondly, IXPs are considered to be parts of the IP/MPLS and the transport network. And finally, we assumed that advertisers and standardization bodies are among supportive organization that exist in the background and provide support for all players.

Our intention behind the development of the Internet ecosystem value creation model was to describe the current value creation activities and the value exchange between the players related to network services. As can be seen from the figure above, in the current situation the IP/MPLS service providers use transport services provided by telecommunication operators and no any other player is involved in this process. Although the IP/MPLS service provider and the telecommunication network (connectivity providers or transport service providers) are physically connected, the interactions and the exchange of values between them are strained by human intervention in the process of network management and network control, as well as low inter-operability resulting from differences in communication languages, switching systems and the multi-standard technology usage.

## 5.5 Case Study

In this section we provide a case study on which we evaluate the impact of MM in the value creation chain of transport service providers. This will help the players involved in the market understand the changes that may arise in relationships after the ONE Adapter has been deployed as a mediator between the IP/MPLS and transport layers.

### 5.5.1 Mediator Model Impact on the Value Creation Model of NSP

The MM architecture is designed to meet the requirements of network operators, and the MM service provider. Specifically, we designed the architecture to allow the IP/MPLS layer and the transport layer to communicate automatically, provide new services such as the IP traffic offloading and automate link/service provisioning.

This implies that MM deployment in the Internet ecosystem will change the value creation model. More specifically, new players will enter into the market, such as IXPs and MM providers. New means of communication will be established, such as MM mediation between the IP/MPLS and the transport layers. New values will be generated, such as automatic provisioning processes. And finally considering the MM deployment location, the IXP role will more be significant than ever before in the new environment. All these effects are shown in the new Internet ecosystem value creation model.

### 5.5.2 New Players' Value Creation Model

Figure 5.11 depicts the value creation model of the MM. The mediator model VCM is based on five value creation activities. The core activities are the management of MM, workflow processing, data collection and storage, and the translation service (OM). The trigger service, which allows the initiation of management operations, has an external interface to the network service providers. The service information flow is represented as out-going arrows and in-coming arrows. Compensation for the use of the MM is also represented as out-going arrows.

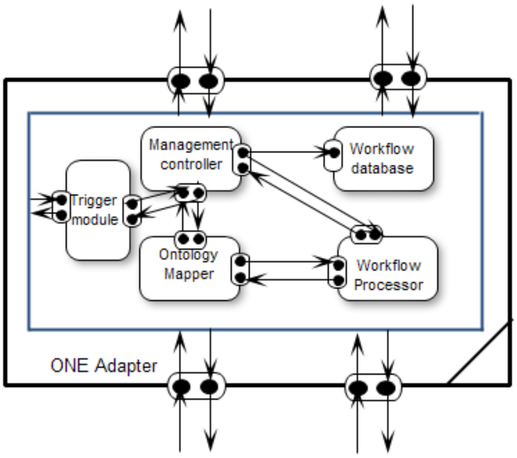



Figure.5.11 MM value creation activities

The role of Internet exchange points becomes significant if we consider the case that the MM can be hosted by the IXP. IXPs are considered trusted entities in the Internet ecosystem. As a trusted entity it is an easy to access and cost effective place to host the MM. Figure 5.12 shows the IXP node which hosts the MM.

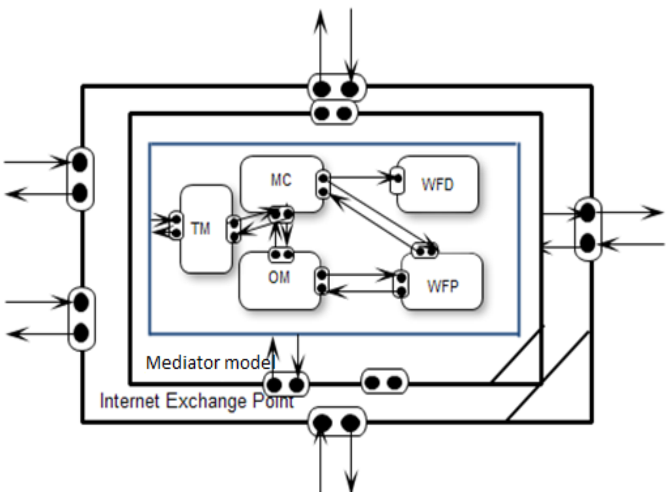



Figure 5.12 IXP node host MM

Mediator model deployment also will change the role of TSPs, moving some of their responsibilities to the management solution providers, namely to the path computation tasks. In the current situation all activities related to path creation are the responsibility of the transport service providers, which has inefficiency of manual network operation. Figure 5.13 shows the telecommunication network (TSP) role in the new environment.

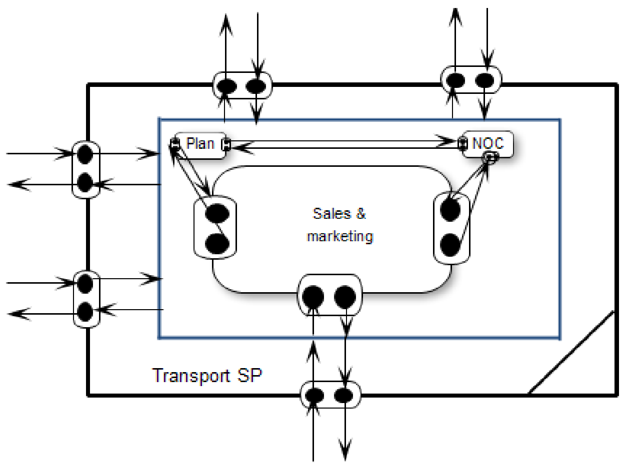



Figure 5.13 Transport service providers new value creation model

As also shown in the figure, the Network Operation Centre (NOC) and the planning department's role are diminished, while the roles of sales and marketing become stronger.

### 5.5.3 Internet Ecosystem's New Value Creation Model

The MM mediation between the IP/MPLS and the transport layer triggers changes in the methods of interaction, as well as in the creation of new business opportunities. Specifically, at least three new business models can be found in the Internet ecosystem value creation model shown in Figure 5.14. These are; MM deployment as a standalone entity, MM hosted by the IXP, and MM operated either by the IP/MPLS or transport layer. In the first scenario (long dashed line area) the IP/MPLS network requests a transport service from MM. To fulfill this demand, the MM starts the execution of the workflow requested, which is supported by the transport network providers as well as by the path computation provider (1, 2, 3, 4, 5, 6, 7). In the second scenario, where we assumed that the MM is hosted by the IXP node, the same request follows paths 9, 10, 11, 12, 13 (black short dashed line).

In the third scenario, where the MM is operated either by the IP/MPLS layer or by the transport layer, the IXP node will not be involved and in this case a new player will enter the market.

Both the first and second scenarios are leads to the introduction of at least one new player which is the IXP with a new function. As can be seen from the figure above, MM deployment as a mediator between the IP/MPLS and the transport layer network management system lead to a change in the way the two layers traditionally exchanged values with each other. More specifically, a IP/MPLS network demand for a new link between the two routers, traditionally served by the transport layer without the involvement of any other player in the Internet ecosystem (Figure 5.10, interfaces 1, 2). This process is slow, error prone and costly as it involves human intervention.

The MM deployment that facilitated automatic interaction and the automatic execution of the service provisioning process changed the way both layers used to communicate. Furthermore, the introduction of the MM in the Internet ecosystem led to the more active role of the Internet Exchange Point and the Path Computation provider role. In the case in which the MM is involved (for instance service provisioning), the request for the service goes to the MM instead of to the transport network management system (Figure 5.14 – 1, 2 or 9, 10). Similarly, the MM uses the PCE provider to compute the path between the two routers in the IP layer (Fig. 5.14 – 5, 6 or 12, 6). This task was traditionally executed by the transport layer and took a long time. Furthermore, in the case in which the MM is deployed at the IXP node, the IXP role then becomes more important than before.

In short, as can be seen from the figure below, three possible business models can be introduced in the Internet ecosystem as determined by the MM deployment between the IP/MPLS and transport layers.

## 5.6 Chapter Summary

This paper analyses the impact of a mediator model between the IP/MPLS network management system and the transport network management system in the value creation of transport service providers. The deployment of MM allows the coordination and automation of functions between the two layers. Similarly, MM deployment triggers changes in the way the two layers exchange their values. Our findings also suggest that at least three new business models can be established depending on the location of MM deployment.

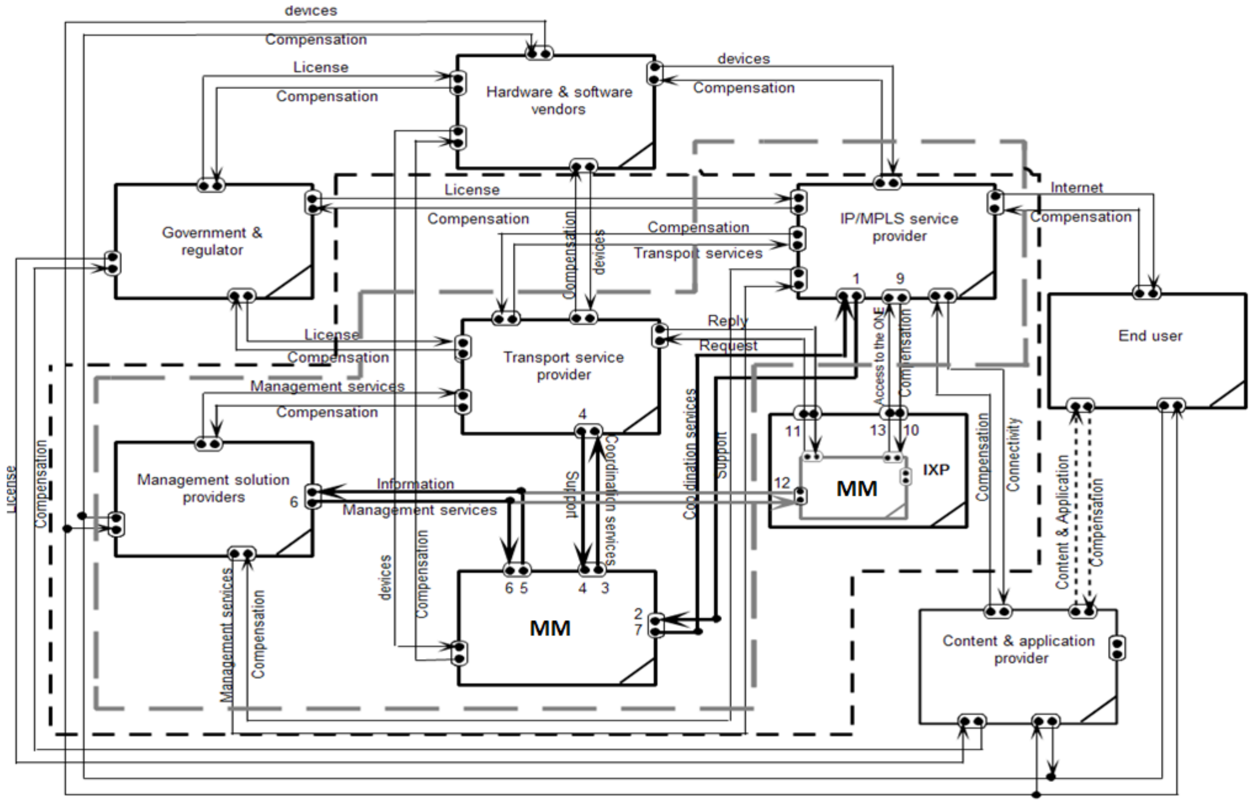



Figure 5.14 Internet Ecosystem new value creation model

# Chapter 6. A User Preference-Based Enterprise Path Computation Algorithm for SDH/SONET Networks

## 6.1 Introduction

In the current environment, where data communication has surpassed voice communication and bandwidth incentive applications such as IP-TV and P2P have become parts of our daily lives, network providers are flooded with bandwidth requirements.

SDH/SONET networks as a major provider of the capacity and connectivity for the lower layer, namely the IP layer, suffers from high operational costs due to its static nature.

Meanwhile, providing differentiated services to enterprise customers has been found to be one of the main sources of revenue for carrier providers [Fawaz et al., 2004]. The increasing demand for bandwidth and the business opportunity to provide network services with the lowest possible provisioning time, suggest that there is a need for an automatic way of path computation. Traditionally, for the provision of a service network the service providers log into the network management system (NMS) and manually carry out provisioning related activities. This process is time-consuming, error prone and costly. As mentioned by Chahine et al. [2004], traditional service delivery passes through sales, administration, project management and network operations, where multiple sub-department employees are involved in the process.

To provision a service, network operators have to consider the requested bandwidth, the required QoS, the available network resources, the non-desirable path identified by the user and the optimal network resource balanced usage. All the above-mentioned requirements need huge inventory evaluation, which may take a long time to come up with a concrete solution.

To allow more accurate, fast and economically efficient path computation, the Internet Engineering Task Force (IETF) introduced architecture for the Path Computation Element [Poter, 1988]. Despite the introduction of the architecture, no standardized implementation exists for path computation. In order to allow automatic path computation one has to accomplish at least three major tasks; inventory information collection, path computation and issuance of the configuration command.

Although the above-mentioned requirements are equally important, in this chapter we propose an algorithm for an enterprise PCE to calculate a pair of disjoint paths between the specified source and the destination node, considering user preferences and network operator's priorities – assuming that the first and the third requirement for an automatic means of provisioning a service currently exists in the NMS functions.

The path computation problem has been studied for quite a long time by scholars and many heuristics have been proposed. So far most of the studies have been done by considering the path computation to be a routing and wavelength assignment (RWA) problem. Scholars have mainly considered a network combination of nodes connected by edges with an integer unit of capacity. They have approached the problem with different assumptions and proposed solutions to address different goals, such as network optimization and cost reduction.

While many of the proposed solutions are found to be a fit for the RAW problems for networks with WDM technology, they are not suitable for the path computation element that has different requirements and goals. Furthermore, in this chapter we propose a specific solution for path computation in SDH/SONET networks, which has an explicit multiplexing structure that needs to be taken into account when providing any solution for computing the paths.

It is worth mentioning that in our approach we differentiate between the RWA problem and path computation. This is because the ultimate goal of path computation as a service is to compute and specify the path or paths between the source and destination nodes considering the QoS demanded. Unlike the RWA approach, path computation as a service is not sensitive to time nor it is responsible for updating the link status database.

Based on our discussion in Chapter 4, where we described the architectural design for the proposed mediator model, the path computation element (PCE) considered in our architecture is responsible for computing and specifying all possible paths between the source and destination nodes and selecting a pair of paths satisfying the user preferences. The activities related to the SLA setup, path reservation, testing and path activation are the responsibility of the transport provider NMS and operators.

The algorithm proposed in this chapter follows 4 main goals. Firstly it must address the SDH/SONET technology requirements. Secondly, it needs to overcome the inefficiency of current practice for finding a pair of disjoint paths by removing the first path from the network topology. Thirdly, it should return a pair of paths considering the user preferences. And finally, it must provide a pair of paths satisfying the network operator’s priorities.

## 6.2 Literature Review

The path computation problem, known as the routing and wavelength assignment (RWA) problem, has been studied by scholars for quite a long time. The problem of searching for a diversely routed path with a shared risk link group (SRLG) was studied by Hu [2003]. He formulated the problem as an integer linear program and showed the effectiveness of the solution for optical networks. A graph transformation technique to address the adaption constraints has been proposed by Jabbari, Gong and Oki [2007]. The technique, called the channel graph, is based on the dual graph which translates each link into a node and adds an edge between the two nodes before performing the shortest path search. An integrated topology independent solution to the RAW problem to minimize the number of hops has been proposed by Janardhanan et al. [2006]. The multi constraint shortest path problem (MCSP) to find a feasible path subject to multiple additive constraints has been studied by Kuipers [2002].

The K shortest path problem has been studied by Zing and Zhao [2008]. They proposed an algorithm to find K number of paths subject to multiple constraints. According to their claim, the algorithm is able to find K number of MCSP for different qualities of service.

A path computation algorithm for the MPLS network has been proposed by Banerjee and Sidhu [2001]. They consider a case in which the request for bandwidth arrives independently. They claim that their algorithm improves network utilization and maintains network stability under high load conditions. SAMCRA [Mieghem and Kuipers, 2004] is a QoS routing algorithm designed for multi constraint path search. It uses foresight information to reduce the search area by cutting off the paths that will not lead to finding a feasible path. An integer linear programming (ILP) formulation has been proposed, and shows that aggregated information usage, instead of complete information usage, is suitable for routing purposes.

It is important to note that a path computation for a specific bandwidth and with the QoS demanded may result in an optimal path for the time being, which means that we should not expect that the change in network traffic will not affect its optimality. Oki and Shiomoto [2005] and Zhang and Ramamurthy [2003] have studied path computation and traffic grooming considering dynamic traffic changes, and proposed different solutions to the problem. An open source path computation element approach called Network Aware Resource Broker (NARB) has been designed and developed by the DRAGON project [Lehman, Sobieski and Jabbari, 2006].

As also mentioned by Textronix [2011], the majority of studies investigating path computation problems have one thing in common. In their studies the researchers have all considered a network which consists of nodes representing the network elements, connected with the fiber links or light paths with an integer unit of capacity. While this is a common requirement that needs to be considered for path computation in networks with WDM technologies, this approach does not work for SDH/SONET networks due to their specific multiplexing structure. Furthermore, the majority of solutions proposed so far have mostly addressed the RAW problem. These do not fit for path computation as a service offered by as an enterprise entity which serves the carrier networks as a management solution provider.

## 6.3 User Preference-Based Enterprise PC Algorithm and SDH/SONET Networks', Specific Requirements

### 6.3.1 Enterprise PCE Requirements

The path computation architecture developed by IETF [Kumaki, 2006] is designed to work for control plane frameworks, also developed by the standardization organizations. While the standardized architecture is suitable for any other path computation implementation approaches, presently no standardized approach exists for its implementation. The major differences between the current implementation approaches of PCE and that for an enterprise PCE is firstly computation time.

An enterprise PCE similar to the one considered in the building blocks of our architecture for the mediator module is to serve the IP and transport layers. The enterprise PCE has different requirements to that designed for the dynamic network change. In the case of an enterprise PCE, the time limitation at a rate of milliseconds is no longer a requirement.

This is because the PCE just serves as a path computation provider and sends the result of the path computation to the requester for further processing, such as service level agreement negotiation and IP and transport layers networks element configuration. Secondly, an enterprise PCE should be able to provide multiple options so as to increase the probability of the selection of a pair of paths within the list of all possible paths between the source and destination nodes. And finally, a PCE as an enterprise entity must have the capability to assure the privacy of the information that needs to be sent to the PCE by the IP and transport layers, so as to compute a multi-layer path. The above-mentioned requirements suggest that an enterprise PCE may need a specific algorithm to be able to address a variety of options to meet every network providers' policy related constraints of path selection.

### 6.3.2 SDH/SONET Technology, Specific Requirements

The current architecture of the Internet consists of multiple layers. They are designed to aggregate and map the end users' tiny data packet to the 10 Gbps light paths of transport network links. SDH/SONET is the carrier layer network providing bandwidth services to the IP/MPLS networks. While there are efforts to bypass the SDH/SONET layer and connect the IP/MPLS layer directly to the WDM or DWDM layer, the bandwidth granularities of the SDH/ SONET and the effective resilience mechanisms of SDH/SONET will ensure that this layer exists for a year or more. SDH and the SONET standards have specific multiplexing structures which fit the voice communication channels. Considering the fact that this layer serves as the carrier layer between the IP and transport layers, any path computation solutions should respect the multiplexing structure of SDH and SONET technology to provide a practical solution.

As also mentioned by Ramachandran et al. [2010], the capacity of a SDH/SONET link cannot be considered as an integer unit. Consequently, the available capacity of a SDH/SONET link cannot be calculated as a residual of subtraction from the total capacity to the already assigned capacity, which can be found in many studies. The SDH/SONET link capacity is divided into several types of Virtual Container (VC, called the virtual tributary for SONET technology) to map and multiplex the voice channels which is mostly aggregated in E1 and T1.

Therefore all the requested capacity must fit with one of the standards defined by SDH/SONET. Furthermore, to provision a service with the capacity of approximately 2 Mbps in the SDH network, one needs to create a higher level container, the VC4 trail, which can carry up to approximately 150 Mbps data. In addition, by assigning a capacity of 2 Mbps which is equivalent to a VC 12, the link cannot carry a full VC 4. It is because one VC3 is divided to provision a service with the capacity of a VC12. In short, because of the above-mentioned requirements, the works mentioned in the previous section are not suitable for SDH and SONET networks, and there is a need to provide a solution considering the specific characteristics of the carrier network.

## 6.4 Constraint-Based Path Computation

The applications that QoS demands depend on their nature and characteristics. For instance, some applications such as video conferencing and IP-TV are very sensitive to packet loss, while some others are not. Some applications such as e-mail may tolerate a relatively longer delay, while others require a very short delay.

The above-mentioned and other requirements, which are not mentioned here, are the reasons for the demand for a specific path that meets all required QoS that are constraints for the path computation. Jabbari and Gong [2007] classified the constraints for path computation into two main groups, namely prunable constraints and non-prunable constraints. The authors included bandwidth requirements, policy constraints and protection requirements in the prunable group. They subdivided the non-prunable constraints into additive constraints, which include constraints such as attenuation and cross talk. In the non-additive sub-group they include constraints such as label continuity and switching capability.

Most of the solutions mentioned in the literature review section of this chapter try to address these constraints in one or another. However, it cannot be confirmed that the algorithm they proposed can address all those constraints or that it is able to find a real optimal path addressing all the constraints. The reality is that it is almost impossible to find a path that meets all the requirements of the users and network providers. Network operators always attempt to assign a path for the requested bandwidth demanded that meets their policy, such as the network optimization or administrative costs.

In our case, the provision of an optimal pair of disjoint paths between the source and the destination nodes, we will introduce an algorithm in the next section of this chapter to meet the requirements of SDH/SONET networks as well as an enterprise path computation element.

## 6.5 Proposed Path Computation Algorithm’s Description and Assumptions

The step by step description of our approach is as follows. Firstly, we designed the algorithm to address the demand for the multi-layer path. More specifically, by multi-layer we mean the IP and SDH/SONET layers. The term virtual network is usually used by scholars to represent a network that owns the physical (the transport) infrastructure and uses the lights paths of the WDM layer to connect network nodes to each other. While this is correct for networks with the WDM or DWDM technologies, it is different when we are considering SDH/SONET networks. The difference comes from the multiplexing types of these networks.

The terms WDM and DWDM represent these networks’ multiplexing mechanisms, which is wavelength division multiplexing. In contrast, SDH/SONET networks use TDM, which is completely different from WDM.

In order to connect two routers to each other in the IP layer, we need to create a light path between them in the transport layer with WDM or DWDM technologies. But in the case of SDH/SONET networks, we may need to assign a time slot and create a trail or sequence of trails to fulfill the demand. It means offering a multi-layer path between the IP and carrier layers with the SDH/SONET technology, in which case one needs to consider the topology of trails already existing in the network as well as the topology of the carrier layer network. Moreover, for an enterprise path computation provider it is essential to have the information about the topology and the measurement of both layers.

In this chapter we assume that both layers are capable of providing such information for path computation. Specifically, we assume that the upper layer (the IP/MPLS) runs multi-protocol label switching protocols, and the lower layer (carrier network) uses the recent extension of the routing and signaling protocols for the SDH/SONET networks to collect network information . Secondly, we design the 3MPCE algorithm to find multiple paths addressing the network optimization problem, as well as the constraints defined for the computation. Furthermore, our approach allows us to calculate as many constraints as known for every path found in the network. This lets a carrier provider select the best fit path considering the QoS demanded as well as their network policies and priorities. Finally, we design the algorithm not only to find the paths which have an available trail but also to find paths in the range of optimal network capacity usage, as well as paths considering the available capacity of the links.

As stated before, SDH/SONET networks impose a specific multiplexing structure that needs to be considered, while providing an automatic path computation solution. To address this requirement, we divided the total available capacity as well as the trail capacity into the numbers of possible VC12 in the link, assuming that the minimum capacity request is equivalent to 2 Mbps. This allows us to search the paths for a specific capacity, such as a VC12, a VC2 which is the equivalent of 7 VC12 and a VC3 which is the equivalent of 21 VC12. The capacity demand for the VC4 will not be searched in the trail topology and goes directly to the optimal available capacity topology before searching the available capacity topology. This is because every time an STM-1, which is the equivalent of a VC4, is created at least one of its three VC3 will be divided to accommodate the bandwidth requested. This means the existing trail does not have the capacity to accommodate a VC4, and consequently the demand for a VC4 capacity always leads to the creation of a new trail in the link or links between the source node and the destination node.

The algorithm is also designed to address the inefficiency of the current approaches for the finding a pair of disjoint paths between the specified nodes. Currently, to find a pair of disjoint paths one need to run the Dijekstra's algorithm to find the shortest path between the source and the destination nodes specified and then remove the path that has already been found in order to find the protection path. This approach does not always lead to the optimal path, between the two routers. This is because by removing a set of links which belong to the first path found, unintentionally we reduce the network's reachability. This means we may lose the opportunity to find a better pair of paths between the specified nodes. The algorithm proposed in this dissertation allows consideration the above-mentioned requirements, and returns a pair of the most optimal disjoint paths.

## 6.6 Scenario and Link Capacity

For the result of our simulation to be more practical, we choose the National Science Foundation network topology which has 14 nodes and 21 adages [NSFnet, 2011].

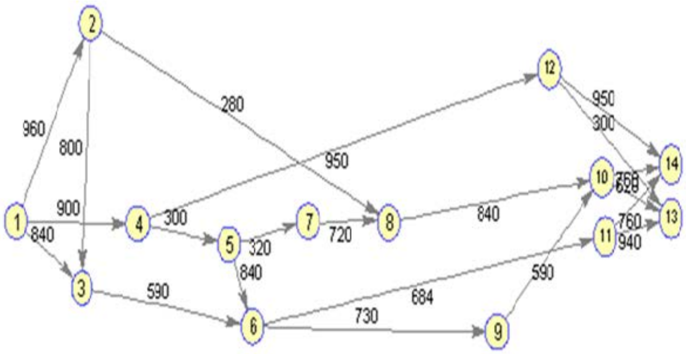


Figure 6.1 NSF net. topology with 14 node and 21 edges

We describe the network as a directed graph. This is because SDH/SONET networks are directed by their characteristics. The SDH/SONET reigns can be single directional, either clockwise or anti clockwise, or two directional, one clockwise and the other anticlockwise. But in any case the links are directional. Furthermore, the purpose of our algorithm is to find the paths between the two nodes in the network searching from the source to the destination, or vice versa which will lead to the same result if they are directional. For the simplicity of our calculations we assumed that all the links in the network will have an initial capacity of STM-16. The number of VC12 that can be carried by a single synchronous transport module one (STM-1) signal, calculated based on the STM-1 frame structure. More specifically a STM-1 frame contains 9 rows and 260 columns, which is also called VC4 in the SDH standard. A VC4 can accommodate up to 3 VC3, each of which can be placed in 9 rows and 85 columns. This means a VC4 can contain up to three VC3s. A VC3 can enclose up to seven VC2, each of which covers 12 columns and 9 rows. And finally, each VC2 can contain up to 3 VC12, which covers nine rows and 4 columns of an STM-1 frame. Based on the multiplexing structure of the SDH standard a single STM-1 signal can carry a capacity equivalent to 64 VC12. In our example case, to calculate the available capacity we subtract the already assigned number of VC12 from the total possible number of VC12 (the initial capacity). The numbers on the links in Figure 6.1 represent the available number of VC12 on each link.

### 6.6.1 Simulation Tool and Simulation Algorithm

We used MATLAB simulation tools to simulate the network shown in Figure 6.1 and to run our experiment. Furthermore, to find all possible paths between the source and the destination nodes specified, we call the Breast-First-Search algorithm. The steps below listed describe the algorithm for searching a pair of disjoint paths, considering the user preferences and the network operator's priorities.

The objective of the algorithm is to find a pair of disjoint paths between the specified source and the destination nodes, satisfying the user preferences as well as the network provider preferences. The algorithm is designed to address the multiplexing structure of SDH/SONET technologies as well as to overcome the inefficiency of the current approaches for finding a pair of disjoint paths between the specified source and the destination node.

Specifically, the algorithm shown below has four major advantages over similar algorithms proposed to compute paths between two routers in the IP layer. Firstly, the algorithm is designed to address the multiplexing structure of SDH/SONET technologies, as SDH/SONET technology imposes a strict multiplexing structure that needs to be considered when proposing any automatic way of path computation. Secondly, the current practice of finding a pair of disjoint paths by removing the first path found from the network topology and searching for the protection path, may lead to a loss of opportunity to find a more reasonable pair of disjoint paths. The algorithm introduced below allows to us to select a pair of paths among all possible paths between the specified nodes, which will result in finding the best fit and best possible optimal path. Thirdly, by considering three different sub-topologies (network topology with the links with available trail, optimal available capacity sub-topology and the available capacity sub-topology) the algorithm allows network operators to protect network resources from fragmentation, as well as provides the opportunity to provision new links considering optimal network resource usage. Fourthly, the algorithm is designed to find a pair of paths satisfying the user preferences while taking into account the network operator's priorities.

**Inputs:**

The below listed input parameters are considered to be the most important parameters for the path computation in SDH/SONET Networks, which are considered in our approach.

<u>Network topology information,</u>

- Network connectivity matrix, which describes how nodes are connected to each other.
- Links Initial Capacity, which describes the initial capacity in the link.
- Links Allocated capacity, which describes the capacity that already allocated to the users.
- Links lengths, which describes the distance between every start node and the sink node.
- Links round trip delay, which describes the duration of time between sending the first packet of information and receiving the first reply packet from a source node to a sink node "propagation delay"
- Links trail availability, which describes the available trail in the link.
- Links packet losses, which describes the percentage of the packets that may loss while transmitting information between the nodes.

User requirements,

- Demanded bandwidth which is the number of VC12, (the bandwidth a user demands between the two routers at the IP layer)
- Customer preferences, which describes the preferred by the user path, such as low cost, low delay.
- Source and destination nodes, which describes the start node and the sink node that the path between them needs to be find.

**Outputs:**

The algorithm designed to return:

- A pair of disjoint paths between the specified nodes considering firstly, the user preferences, and then the network operator preferences.
- The disjoint paths QoS parameters:
  - Paths length (Km),
  - Paths packet losses (%)
  - Paths roundtrip delay (μs)
  - Paths bandwidth normalized length (Km/VC12)
  - Number of hopes traversed (integer)

**Abbreviations used:**

G(V, E): Network graph with (V) representing nodes and (E) representing edges.

T: Describing the availability of a trail in the link.

Tc: Vector describing the trail capacity.

Tst: Trail sub-topology (Network topology with the links having a trail available).

Tb: A Vector describing the capacity of the existing tail in the links.

OAC: Optimal Available Capacity sub-topology (Network topology with the links having the capacity higher than 30% of its initial capacity).

ACT: Available Capacity sub-topology (Network topology considering the available capacity in the links)

Cx: Capacity demanded (demanded bandwidth "number of VC12" between the specified source and destination nodes)

S: Source node (start node)

D: Destination node (sink node)

L: links length in (Km)

De: Round trip Delay (The time starting from the first packet sent till the first response packet received)

Pl: Packet losses (The percentage of data packets that may lose during the transmission process)

Lb: Bandwidth normalized length (Describes both the links length and the its wideness)

Nh: Number of hopes (describes the traversed nodes from source to destination)

X: User preferences (preferred path by the user such as; low cost or low delay path)

IC: A vector describing initial capacity (initial number of VC12 assigned in the links)

AC: A vector describing number of VC12 already allocated from the total capacity of the links.

PF: Path list (Preferred to the user paths)

### 6.6.1.1 Algorithm Description

Consider a network graph G(V, E) with input parameters IC- a vector representing the links initial capacity, AC- a vector representing allocated capacity, T- a vector representing available trail in the links, Tb- a victor representing the trail capacity, and the QoS parameters L- a vector representing the links lengths, De- a vector representing the links roundtrip delay, PL- a vector representing links packet losses, Lb- a vector representing bandwidth normalized path length as well as the user requirements such as the demanded bandwidth between the (S, D) nodes and the preferred pair of disjoint paths.

**Initialization**

1 Generate trail sub-topology (Tst) using the network graph G(V, E), and T #(remove all the links from the network graph which have no trail available)

2 From the Tst graph, remove all links with a capacity Tb < Cx

3 Find all possible paths between the specified S, D nodes, using breadth-First Search algorithm (BFS) the source node and the destination node and add them to the list of paths PF.

4 **For** ί = 1 to n **(**where n is the number of paths in PF)

5 Calculate QoS parameters value $Y_i$ for path ί (Sum QoS parameter values for the links belonging to path ί)
6 L (paths lengths),
7 De (Paths round trip delay),
8 PI (Paths packet losses),
9 Lb (Paths bandwidth normalized length),
10 Nh (Number of hopes in the paths).
11 Remove paths with the value less than X
12 **End**

13 Generate Optimal Available Capacity (OAC) sub-topology, from the G (V, E) by removing all links with a capacity <30*IC/100.

14 From the OAC sub-topology graph, remove all the links with a capacity < Cx

15 Find all possible paths between the S, D nodes (using BFS) and add to the list of paths PF

16 **For** ί = n+1 to m **,** (where n-m is the number of the paths in PF)

17 Calculate QoS parameters value $Y_i$ for path ί (Sum QoS parameter values for the links belonging to the path ί)

```
        L (paths lengths),
        De (Paths round trip delay),
        PI (Paths packet losses),
        Lb (Paths bandwidth normalized length),
        Nh (Number of hopes in the paths).
        Remove paths with the value less than X
End

Generate Available Capacity (ACT) sub topology by deducting allocated
capacity (AC) from the initial capacity (IC).

From the ACT sub-topology graph, remove all the links with the capacity
(IC – AC) < Cx

Find all possible paths between the S, D nodes (use BFS) and add to the list
of path PF.

For ί = m+1 to k (where k-m is the number of new paths in PF)

        Calculate QoS parameters value Y_i for path ί (Sum QoS parameter
        values for the links belonging to path ί)
        L (paths lengths),
        De (Paths round trip delay),
        PI (Paths packet losses),
        Lb (Paths bandwidth normalized length),
        Nh (Number of hopes in the paths).
        Remove paths with the value less than X
End

For ί =1 to k
        For j = ί  to k
                 if path ί of PF and j of PF are disjoint
                                Sum QoS parameter values Z of the pair of path ί
                                and j
                                Add pair of disjoint paths with the sum of QoS
                                parameter values Z to the list of disjoint paths DP
                End
        End
End
Lowest value of QoS parameter = max integer
For ί = 1 to k (where k is the number of paths in DP)
        If (lowest value of QoS parameter > Z_i)
                Lowest value of QoS parameter = Z_i
                Lowest value path = ί
        End
End
Return (lowest value of QoS parameter, DP_lowest value path)
```

### 6.6.2 Simulation Variables

Table 5.1 shows the variables selected for our simulation. The 9 variables described in the table below are the link total capacity (TC) which is assumed to be equivalent to STM16 capable of carrying a 2Gbps signal as an initial capacity, the link available capacity (AC) which is randomly set between 500Mbps to 2000Mbps for each link (280 to 950VC12), the trail capacity (TRc) which is equivalent to a STM1 signal that can carry up to 64 VC12, the available trail (AT) which is randomly set for the links in the range of 0 and 1 (yes or no), the packet losses which are assumed to be as high as 0.04 percent per kilometer, the link's length which is selected in order to maintain the network model shape, the links round trip delay which is considered to be 5µs per kilometer fiber plus 30% transmission delay to cover the delay reasoned by the information processing, and finally the bandwidth normalized link's length which helps to find wider paths in the case where two or more paths are found with the same requirements specified.

Table 6.1 Simulation variables, variables range and descriptions

| Variable | Range | Description |
|---|---|---|
| Link total capacity (TC) | STM16 | Equivalent of 1040 VC12 which can carry 2,045.376 Mbps |
| Link available capacity (AC) | 500Mbps-2000Mbps | Equivalent of 280-950VC12 |
| Trail capacity (TRc) | 0-150.336Mbps | 0 to 64 VC12 |
| Available trail | 0-1 | Yes-No |
| Packet losses | Percent/Km | 0.04 % per Km |
| Links length | Km | Edge's lengths selected such that to keep the network shape |
| Links round trip Delay | 5µs | 5µs/Km+30% Process delay |
| Links bandwidth Normalized length | Km/Vc12 | L/AC |

Among the all constraints discussed in the previous sections we consider 4 to be specifically relevant to SDH/SONET technology. Constraints such as wavelength continuity and label continuity are not relevant to SDH/SONET. Furthermore, we consider packet loss as addressing two other constraints as well, that is the attenuations and jitter which lead to packet losses. The link’s length, considered as a variable in Table 4, can also address the administrative cost. The round trip delay and the link’s bandwidth normalized lengths are the other two important variables that are included.

## 6.7 Algorithm Application on NSF net. Topology

To describe how the algorithm executes its tasks, we consider an example path computation case. In this example, we assume IP network operator demand a pairs of disjoint path between the two routers at the IP layer. To fulfill the request, transport network operator, needs connection between the node number 1 and 13 (NSFnet. topology graph). Furthermore, we assume that the bandwidth demanded is equivalent of 7VC12 and that the customer prefers a low cost pairs of disjoint paths between the specified nodes. Notwithstanding, interpretation of low cost paths depends on the network operators policy and priorities. While the shortest distance between the specified source node and the destination node always considered being the low administrative cost path, network operators consider many other factors such as the network balance usage, most demanded roots, while pricing the network capacity. For simplicity, we assume that the low cost path is the path which needs the lowest administrative cost for the network operator.

The first step in our simulation experiment is to find all possible paths between the specified source and the destination nodes, considering the links with an available trail with the sufficient capacity to fulfill the demand.

To do so the algorithm removed all links that have no trail available, or have less available capacity than demanded. Figure 6.2 shows the topology of the simulated network identifying the links with sufficient trail capacity to fulfill the demand.

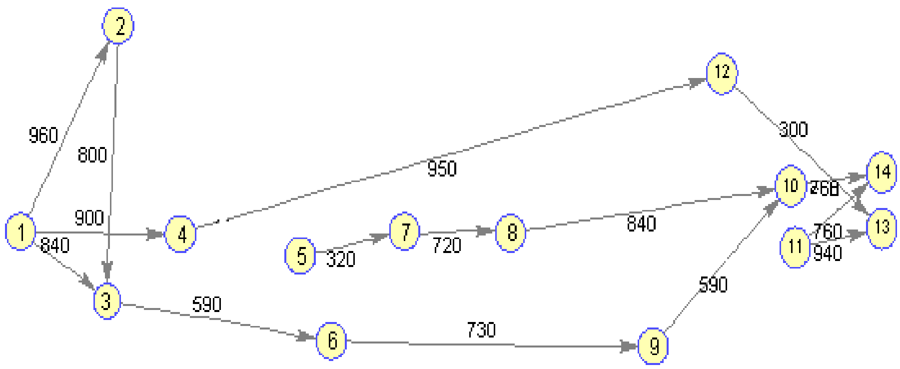



Figure 6.2 NSF net. trail sub-topology graph

It is further important to mention here that the links shown in the figure above include all links which have a trail with both available capacity and optimal capacity.

The path we are searching for in our experimental network is between node "1" and node "13". To find all possible paths between the specified nodes we use the Breast-First-Search (BFS) algorithm. The search found that only one path exists between the nodes (1, 13) with a trail capacity sufficient to fulfill the demand, the parameters of which are calculated and shown in Table 6.2.

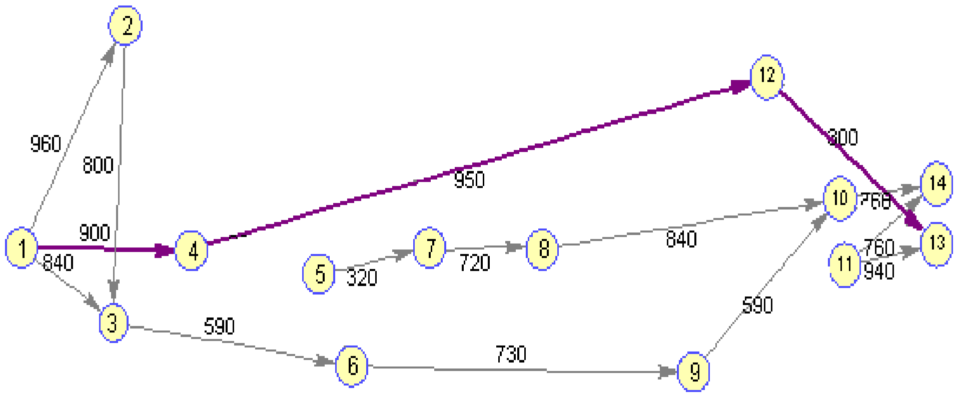



Figure 6.3 A path found between the nodes (1, 13) on the trail sub-topology

According to the result of the search, there are three hops in the path between the specified nodes. The maximum path capacity is equivalent to 300 VC12. It has a length of 110 km and the total packet loss of this link is 4.4 with a delay of 715 microseconds.

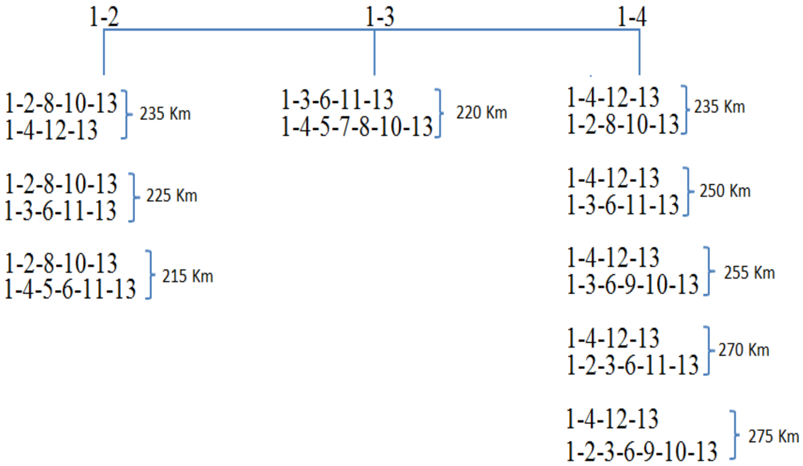
To find other possible paths, the algorithm moves to the next step and searches for paths on the optimal available capacity sub-topology. To achieve that, firstly we generate the OAC sub-topology of the NSF model network by removing all the links that have less capacity than 30% of their initial capacity. We also remove all links from the network topology that have less capacity than demanded before running the BFS. Here, OAC sub-topology means that all the links must have a capacity greater than the 30% of their initial capacity. This, insure network protection against node and link overload and congestion.

As table 6.2 suggests, there are four paths found between the nodes (1, 3) in the second round of the search. Those are the paths (1-3-6-11-13), (1-2-3-6-11-13), (1-3-6-9-10-13), and (1-2-3-6-9-10-13). The algorithm calculates paths QoS parameters, after it found all possible paths. It remove paths which does not satisfies the user preferences, and add the remaining paths into a separate list for further processing, before moving to the next step of the search.

The next step of the search is to find all possible paths between the specified source and the destination nodes (in our example case 1, 13) considering the available capacity sub-topology network. Based on the result, there are 9 paths found between the source and destination nodes specified. Those are (1-4-12-13), (1-2-8-10-13), (1-4-5-6-11-13), (1-4-5-6-9-10-13), (1-4-5-7-8-10-13), (1-3-6-11-13), (1-2-3-6-11-13), (1-3-6-9-10-13), (1-2-3-6-9-10-13). After, the algorithm calculates QoS parameters, remove paths with lower than the demanded QoS and add the remaining paths into the list.

In the next step, the algorithm finds all possible pairs of disjoint paths among all possible paths between the source and the destination nodes. Afterward, algorithm add user preferred QoS parameters of both paths (in our example the distance) to find a pair of paths which most satisfies the user preferences.

As shown in the graph below, there are 9 possible pairs of paths between the node 1 and 13 among which the algorithm must select a pairs of path that best satisfies the user demand.




There are three neighboring nodes from the source node (1) that can be used to reach the destination node 13. Those are nodes number 2, 3, and 4. Among all possible paths, between the source nodes numbers (1) and the destination node number (13), there are 9 possible pairs of disjoint paths that can be considered as the candidate paths.

In our example case, the preferred by the user path is the paths having the lowest cost (shortest distance). Among 9 possible disjoint pairs of paths, found between the specified nodes, paths (1-2-8-10-13), and (1-4-5-6-11-13) have the lowest sum of distance than the others.

Compared with the current practices, if we run the shortest path first algorithm to find the first path considering paths length, path (1-4-5-7-8-10-13) with total lengths of 100 Km will be found. After removing the mentioned path from the network topology graph, the next shortest path that can be found is the (1-3-6-11-13) with the total distance of 120 Km.

Considering the fact, that the two paths found must be dedicated to the user, the first one as the active path and the second one as the protection path, the total cost of pairs of disjoint path request, is the sum of length of the two paths that must be multiplied by the cost pre-kilometer. And so, as can be seen from the table 6.2, the total lengths of the two paths mentioned above is equal 220 Km.

Compare with the current practices, the two disjoint paths selected among all possible paths between the source node 1 and the destination node 13 by the proposed algorithm have 5 Km less length in total than the paths found by traditional way of computing disjoint path.

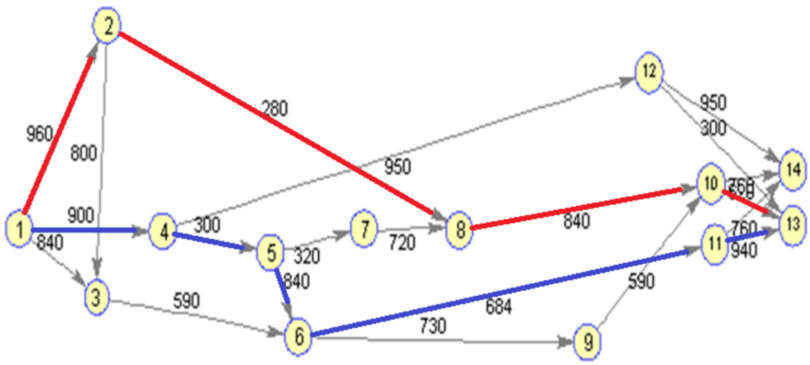



Figure 6.4 A pair of disjoint paths selected among the list of all possible paths

As shown in table 6.2, pair of disjoint paths with the capacity of 7Vc12 and with the lowest distance to the destination node (preferred by the user) is found. The paths mentioned above are belongs to the optimal available capacity sub-topology. The two paths found are P2 and P3 shown in the table1and described in the figure below.

Table 6. 2 Searched paths' characteristics
(S,D – Source, destination, PMC- Path Maximum Capacity,
L- Total Path Length, PL- Total Packet loss)

| Source, Destination Node (S, D), QoS demanded | Paths Number | Paths Description | Number of Hopes | Paths Maximum Capacity (Vc12) | Paths Length (Km) | Paths Losses (PL) (%) | Paths Delay (µs) | Length/ Bandwidth |
|---|---|---|---|---|---|---|---|---|
| (1-13) Capacity Demanded 7VC12 User Preferred Path Low cost path | 1 | Trail | 3 | 300 | 130 | 5.2 | 845 | 0.433 |
| | 2 | Optimal Ac | 4 | 590 | 120 | 4.8 | 780 | 0.203 |
| | 3 | Optimal Ac | 5 | 590 | 125 | 5 | 812 | 0.212 |
| | 4 | Optimal Ac | 6 | 590 | 145 | 5.8 | 942 | 0.246 |
| | 5 | Optimal Ac | 6 | 590 | 150 | 6 | 975 | 0.254 |
| | 6 | Ac | 3 | 300 | 130 | 5.2 | 845 | 0.433 |
| | 7 | Ac | 4 | 280 | 105 | 4.2 | 682 | 0.375 |
| | 8 | Ac | 4 | 590 | 120 | 4.8 | 780 | 0.203 |
| | 9 | Ac | 5 | 300 | 110 | 4.4 | 715 | 0.367 |
| | 10 | Ac | 5 | 590 | 125 | 5 | 812 | 0.212 |
| | 11 | Ac | 5 | 590 | 140 | 5.6 | 910 | 0.237 |
| | 12 | Ac | 6 | 320 | 150 | 6 | 975 | 0.469 |
| | 13 | Ac | 6 | 300 | 100 | 4 | 650 | 0.333 |
| | 14 | Ac | 6 | 590 | 145 | 5.8 | 942 | 0.246 |

### 6.7.1 NSF net. Model Simulation Result

To present a better picture of our algorithm's performance, we ran it 20 times by randomly selecting the source and the destination nodes, as well as the capacity demanded. While the algorithm allows us to automatically update the input parameters after the selection of a pair of paths, we kept this function manual. This is because the enterprise path computation provider goal is to find the best fit path considering the QoS parameters, the capacity demanded, the user preferences and the network operator's policy and priorities. Figure 6.5 shows the paths found in 20 searches on different NSFnet sub-topologies, namely the available capacity topology, the optimal available capacity topology and the trail topology. Accordingly, at least one path was found between the specified source and destination nodes in every search. In 9 out of 20 searches at least two paths were found, either in the same topology or in different network topologies. And in 7 out of 20 searches at least three paths were found.

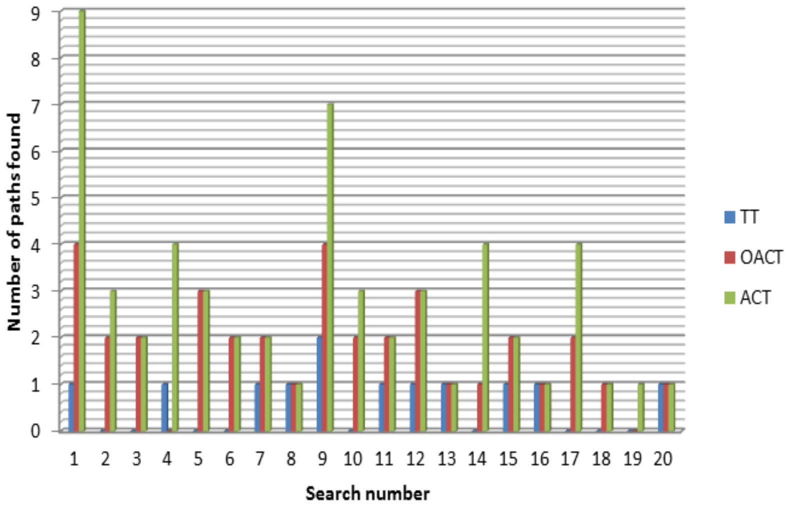



Figure 6.5 Paths found in 20 searches in the three sub-topologies of NSFnet model

The results also suggest that our goal has been achieved. More specifically, our main objective was to find paths in different network layers, namely the IP layer and the transport layer. As can be seen from the figure above, in all 20 searches at least one path has been found between the specified source and destination nodes. In 19 out of 20 searches more than one path was found, and in 14 out of 20 searches more than 3 paths have been found.

Secondly, we aimed to find all possible paths between the specified source and destination nodes and then select a pair of paths satisfying the user preferences and the network operator’s priorities. This was also achieved as all the paths selected satisfy the user preferences and in most of cases the network operator’s priorities are satisfied.

As can be seen in Tables 1.1–1.5 in Appendix (A), each path has different characteristics. They are different in the network layer, or different in level (optimal capacity level or available capacity level), or different in terms of path parameter, such as packet losses, path lengths and path round trip delay time.

In short, the algorithm efficiency is calculated, in terms of blocking rates of three different sub-topologies, based on Equation (8).

$$BR = \frac{Total\ failed}{Total\ numbe\ of\ search}$$

Equation 8

And the ration of disjoint paths to the total request paths, calculated based on the equation 9.

$$DP = \frac{Total\ Disjoint\ path\ found}{Total\ search}$$

Equation 9

Table 7 shows the results of our calculation for blocking rates. According to which the trail topology blocking rate for NSFnet is 0.4, which is the highest among all three. This failure does not mean that that algorithm was not able to find paths, but it means that in 60% of search cases in the trail sub-topology no path existed between the source and destination nodes specified.

Table 6.3. Blocking Rates of NSFnet. sub-Topologies

Trail Topology (TT), Optimal Available Capacity Topology (OACT)
Available Capacity Topologies (ACT)

| Topology | Total number of request | Path found | Path failed | Blocking rate | Total disjoint path found | Ration of disjoint /total |
|---|---|---|---|---|---|---|
| Trail topology | 20 | 12 | 8 | 0.4 | 11 | 0.55 |
| Optimal Available Capacity | 20 | 36 | 1 | 0.05 | | |
| Available Capacity | 20 | 56 | 0 | 0 | | |
| Total number of paths | | 104 | 9 | | | |

Figure 6.6 shows the changes in total blocking rate in each topology. According to which, as the blocking rate declines the number of paths found increases.

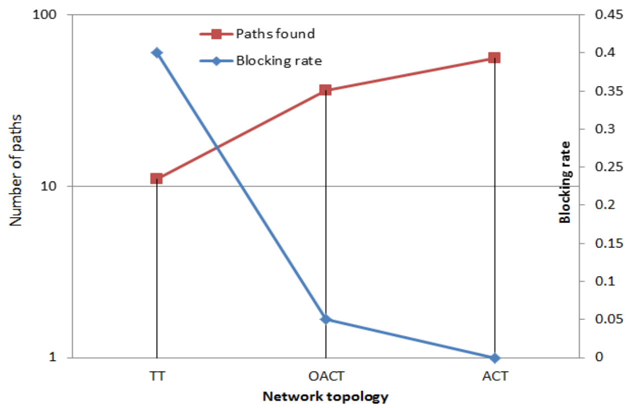



Figure 6.6. Blocking rates and the number of paths found in the NSF net.

While the figure above represents the three different sub-topologies of the same network, it proves the importance of the network topology. Better network design leads to a lower blocking rate.

Table 6.4 shows the average path lengths and the average packet losses, considering the number of hops traversed for each path. According to which paths that traverse two hops to reach its destination node have an average length of 52 Km and average packet losses of 2 percent. In general, the data in Table 8 suggests that the average path length and average packet losses increase as the number of hops increases.

Table 6.4. Average path lengths and average packet losses (NSFnet)

| Number of hopes | Average paths length | Average packet losses |
|---|---|---|
| **2** | 52 | 2 |
| **3** | 83 | 3.3 |
| **4** | 94 | 3.8 |
| **5** | 108 | 4.3 |
| **6** | 118 | 4.7 |
| **7** | 140 | 5.6 |

Figure 6.7, which is based on the data presented in the table above, suggests that as the number of hops traversed to reach the destination point increase, the path length increases. This phenomenon can be clearly seen in the figure below.


Figure 6.7 Average path lengths (NSF net.)

The paths' average packet losses (Figure 6.8), depends on the number of hops traversed, take the same shape as Figure 6.7. This is because the path lengths and packet losses are proportional to each other.

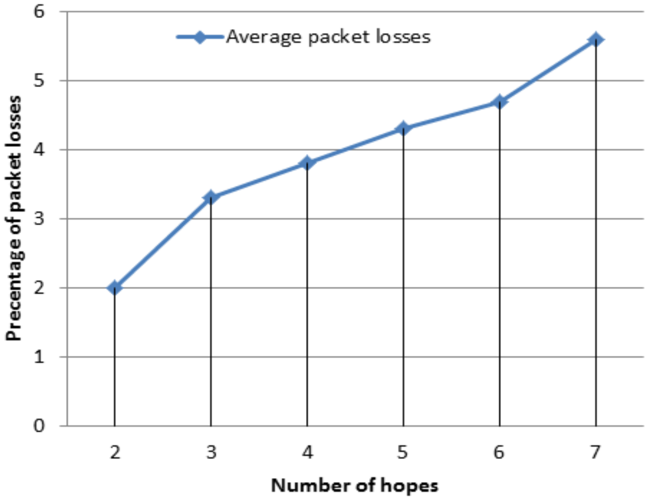



Figure 6.8 Average packet losses of the paths found in the NSF net.

Figure 6.8 clearly shows that on average path packet losses increase as the path traverses a greater number of hops to reach its destination. More specifically, a path that only traverses two hops to reach its destination has average packet losses of 2 percent in our experimental network. The path losses increase by up to 5.6 percent as the number hops traversed increase to 7.

Of course in a real situation the above-mentioned losses depend on the real network information, namely the lengths between the network nodes as well as the average packet losses of each link.

## 6.8 Algorithm Application on European Network Topology

In order to test the algorithm's performance on networks with different topology graphs as well as with different number of nodes and edges, we simulated two other real networks, namely the European network and the German network. In this subsection we describe the results of our experiment on the European network topology.

### 6.8.1 European Network Model

The European network COST, 266/LION, [2011], which consists of 28 nodes connected by 41 edges with a minimum node degree of 2 and maximum node degree of 5, is the second model we choose for our simulation purposes.

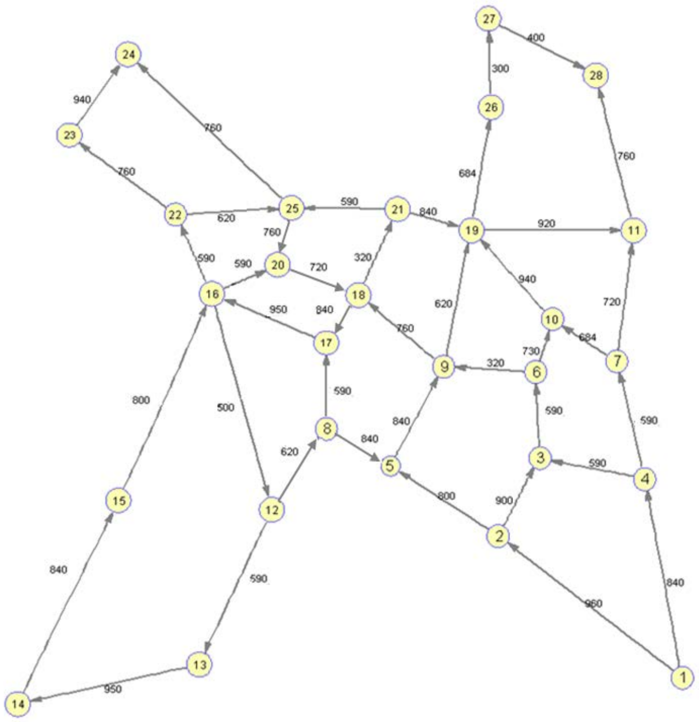



Figure 6.9. European network topology graph
with 28 nodes and 41 edges [COST 266/LION, 2011]

To compare the algorithm’s performance found in the previous sub-section, we considered the same variables and assumptions for the European network. The figure shown above represents the network with the available capacity shown on the links between the nodes.

The difference between the second simulated model (European network) and the first (NSF network) is the number of nodes, the node degree and the network topology design. As can be seen from the figure 6.9, the nodes are distributed in order to cover all areas, but the challenge is to make the network nodes equally accessible to each other.

Same as we did for the NSF network, the first step is to generate the trail capacity sub-topology and then find all possible paths between the specified source and destination nodes. To do so the algorithm removed all the links which have no trail available. Figure 6.9 shows the trail topology of the simulated network.

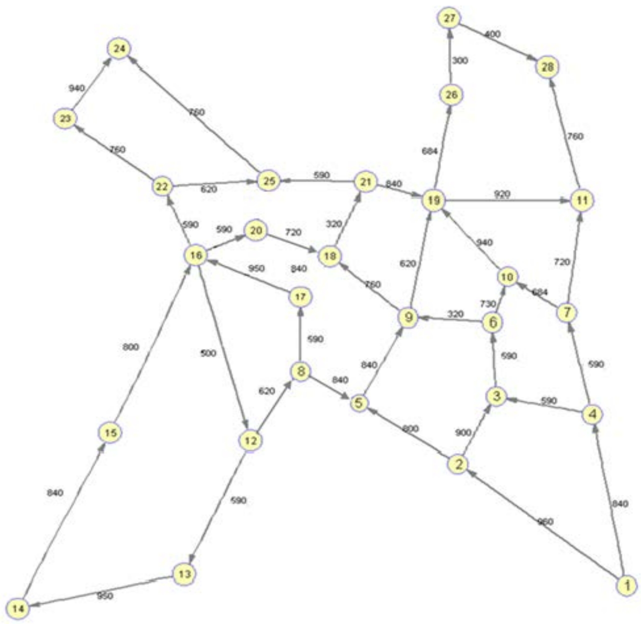


Figure 6.10 European network topology with the trail capacity

In this step, two links are removed from the network topology as they had no trail available, based on the variable table, namely the links between nodes 17 and 18, and 20 and 25. Table 2.1 of Appendix A shows the results of the search for the paths in this sub-topology, which is performed after the sub-topology has been generated.

Figure 6.11 shows the European network topology considering the optimal available capacity, which is the combination of links with a capacity greater than 30% of the initial capacity of the links. As also stated before, we did so to consider the network’s peak load with the assumption that in traffic peak the load will on average increase by 30% in all links.

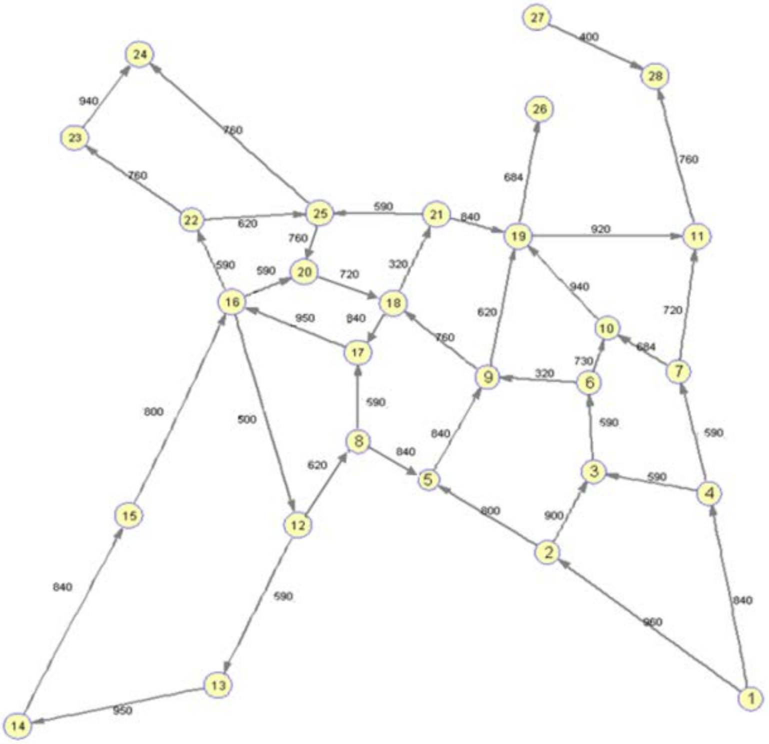


Figure 6.11 European network topology, with the optimal available capacity

As can be seen from 6.11, links with less than the 30% of its initial capacity have been removed from the topology. Specifically and as also shown in the figure above, the link between nodes 26 and 27 has been removed. The paths found in this sub-topology and the path parameters calculated are shown in Tables 2.1–2.5 of Appendix A.

### 6.8.2 European Network Simulation Result

From the results of 20 searches for each sub-topology network shown above, a total of 138 paths were found between the specified nodes. Tables 2.1–2.4 in Appendix A show the detailed specifications of the paths found.

Figure 6.12 shows the paths found in 20 searches for the different sub-networks of the European network topology, namely the available capacity topology, the optimal available capacity topology and the trail topology. According to which at least three paths have been found between the specified source and destination nodes in every search. In 17 out of 20 searches more than three paths were found, either in the same topology or in different network topologies. And in 11 out of 20 searches at least 6 paths have been found.

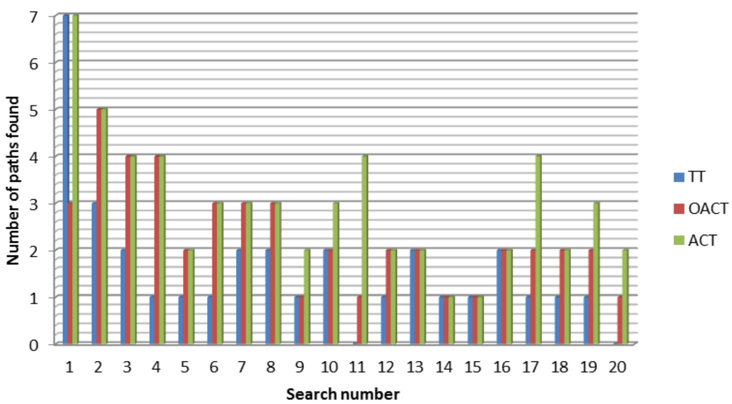



Figure 6.12. Total number of paths found in 20 searches in the sub-topologies of European network model

As shown in table 6.5 below, in 20 searches 33 paths were found in the European network trail topology, 46 paths in the optimal available capacity topology and 59 paths in the available capacity topology. Similarly, 2 searches for paths between the source and destination nodes specified failed to find any path in the trail topology. In both the optimal available capacity sub-topology and available capacity topology the search for paths never failed in 20 searches.

Table 6.5 Characteristics of the Paths Found in European Network

| Topology | Total number of request | Path found | Path failed | Blocking Rate | Total Disjoint paths found | Ration of Disjoint to the total |
|---|---|---|---|---|---|---|
| Trail topology | 20 | 33 | 2 | 0.1 | 15 | 0.75 |
| Optimal Available Capacity | 20 | 46 | 0 | 0 | | |
| Available Capacity | 20 | 59 | 0 | 0 | | |
| Total number of paths | | 138 | 2 | | | |

From the results of the search to fulfill the requirements, 15 requests have been served successfully, while 5 out of the 20 returned with no disjoint path when considering the preferred path of the user. And finally the ratio of disjoint paths to the total number of search suggests that in 75% of cases the algorithm successfully found a pair of paths between the specified nodes when considering user preferences.

The algorithm's inefficiency in terms of blocking rates was calculated based on Equation (8), the results of which are shown in the table 6.5.

As shown in the table above, 1% of searches on the trail sub-topology failed to find a path between the defined source and destination nodes. The ratio of failed to total number of searches for the optimal available capacity is 0, and it is also 0 for the available capacity sub-topology. Figure 6.13 shows the trends in path searches for each sub-topology network of the European network topology.

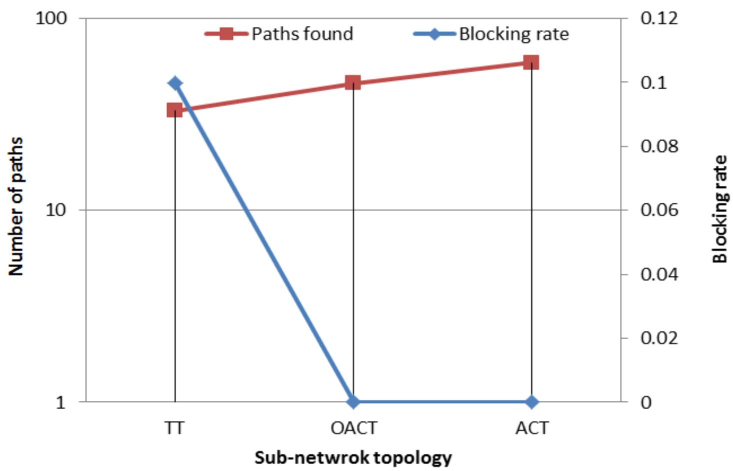



Figure 6.13. Number of path found and the blocking rates of three Sub-network topologies of European network topology

The figure above exemplifies the three different sub-topologies of the European network. The line shapes prove the importance of network topology, as the decline in blocking rate leads to the discovery of a greater number of paths in each layer. Table 12 shows the average path lengths and the average packet losses, considering the number of hops traversed for each path for the sub-topologies of TT, OACT and ACT. According to which paths that traverse two hops to reach its destination node have an average length of 10.6 km and an average packet loss of

3.2%. In general, the data in Table 11 suggests that the average path length and average packet losses increase as the number of hops increases.

Table 6.6 Average path lengths and average packet losses (EU Network)

| Number of hopes | Average Length | Average Packet losses |
|---|---|---|
| 1 | 10 | 0.4 |
| 2 | 20 | 0.8 |
| 3 | 34 | 1.36 |
| 4 | 44 | 1.76 |
| 5 | 50 | 2 |
| 6 | 60 | 2.4 |
| 7 | 77 | 3.08 |
| 8 | 80 | 3.2 |
| 9 | 120 | 4.8 |
| 10 | 140 | 5.6 |
| 11 | 110 | 4.4 |
| 12 | 120 | 4.8 |

Figure 6.14, which is based on data from the table above, suggests that as the number of hops traversed to reach the destination point increases, the average path length increases. This phenomenon can clearly be seen from the figure below.

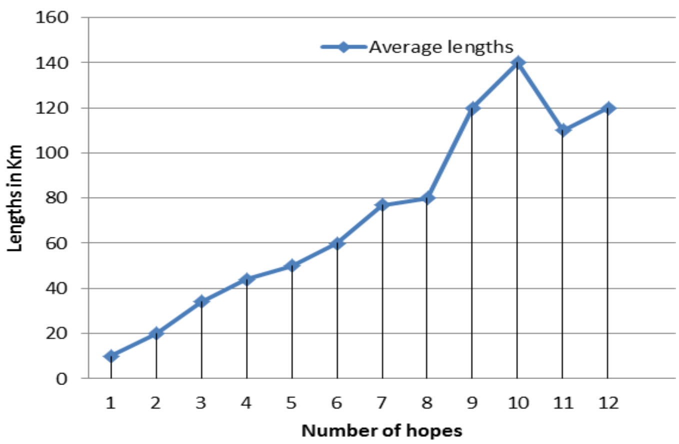



Figure 6.14 Average paths length for the paths found in the European network model

As can be seen from the figure, in one case 11 hop path presents a lower length compared to a 10 hop paths. This phenomenon is can be interpreted as in average the 11 hop paths, has shorter lengths than the 10 hop paths.

The packet losses take a similar shape. As stated before this is because we consider packet losses to be proportional to path lengths. Figure 6.15 shows the average path losses depending on the hops traversed each path.

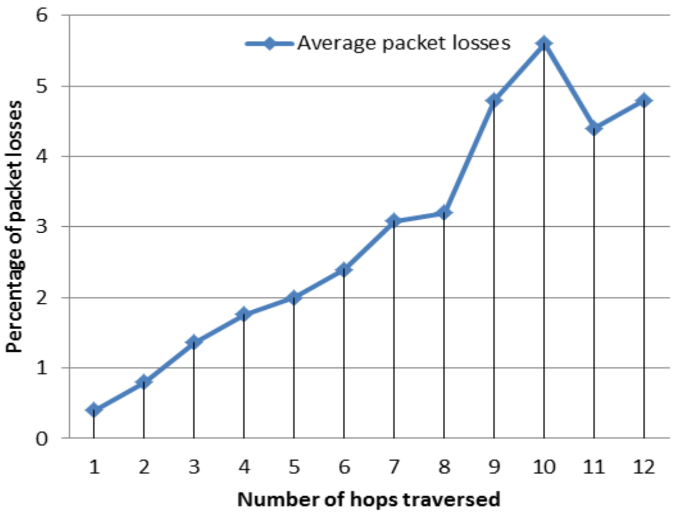



Figure 6.15 Average packet losses of the paths found in EU network model

Similar to the previous figure interpretation regarding the points 11 can be done here in this figure. In addition, as the packet losses are assumed to be proportional to path lengths, this figure also shows the reduced percentage of packet losses compared to the point 10 for the path with 11 hops.

The total number of paths found for each sub-topology and the number of disjoint paths found in every search are shown in Tables 2.1–2.5 in Appendix A.

## 6.9 Algorithm Application on German Network Model

We used the German network topology as our third model. By running the algorithm on the German network topology we aim to evaluate the performance of the algorithm on networks with different characteristics. In this section we describe the results of our experiment on the German network topology.

### 6.9.1 German Network Model

The German network [Zhu and Mukherjee, 2002] consists of 17 nodes connected by 26 edges, with a minimum node degree of 2 and maximum node degree of 6, and it is the third model we choose for our simulation. Figure 6.17 shows the German network topology.

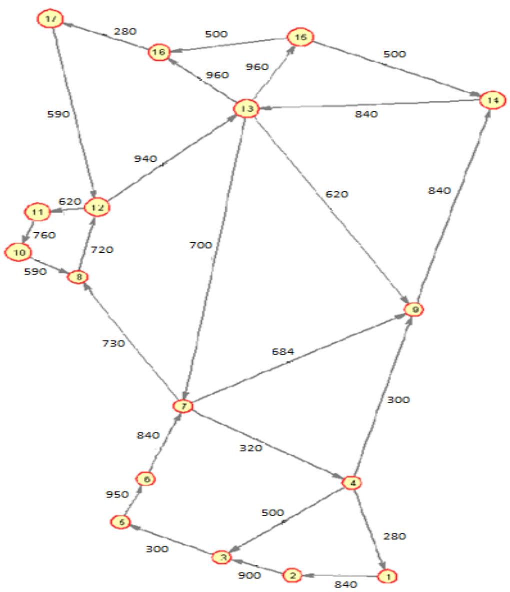


Figure 6.16 German network topology graphs, with assigned bandwidth and directional links
[Zhu and Mukherjee, 2002]

To compare the algorithm’s performance found from the previous two network models with that of the German network topology, again we used the same variables and assumptions.

The figure shown above represents the network with the available capacity shown on the links between the nodes.

The difference between the first and the second simulated model (US network topology and European network topology) and the German network model is the number of nodes, the node degree and the network topology design. As can be seen from the figure above the nodes are distributed to cover all areas. The link directions are set in order to make the network nodes equally accessible to each other.

As conducted for the NSFnet network and the European network, the first step is to find the sub-network topologies, namely the trail sub-topology. Figure 6.17 shows the German network trail sub-topology.

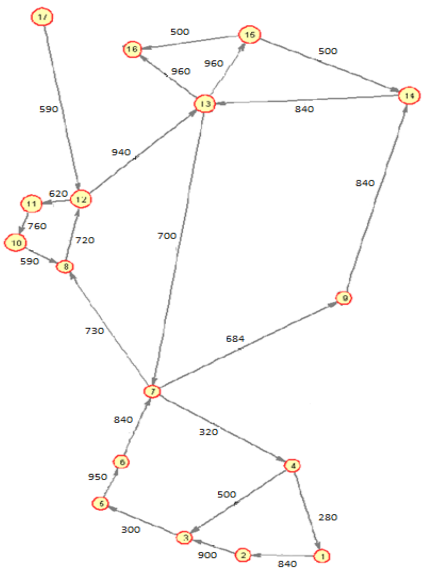



Figure 6.17 German network trail sub-topology

The links removed from the network topology either have no trail on them or had too little capacity left. As can be seen from the figure above, the links between nodes 16 to 17, 4 to 9, and 9 to 3 were removed from the network to fulfill the bandwidth demanded using trails already created by the link. After the trail sub-topology has been created, the algorithm searches for all possible paths between the specified source and destination nodes, and calculates the path parameter before moving to the next step of the search. The same process repeats for the OAC sub-topology and the AC sub-topologies before path selection.

The last part is to select a pair of disjoint paths between the specified nodes, considering the user preferences and the network operator's priorities. In this part the algorithm selects a path among the paths belonging to the trail sub-topology (if it exists) and compares it with all others paths in the list, so as to find the second path. If no path is found that is completely disjointed to the selected path, then the algorithm selects a new path from the list as the candidate path and compares it with all other paths on the list. The algorithm continues the search for the disjoint pair of paths until a pair of disjoint paths has been found or all paths have been checked. In return, the algorithm either introduces a pair of disjoint paths that satisfies the user preferences or informs the user that no disjoint paths have been found, with respect to the user preferences in which case the preferences must be changed.

### 6.9.2 Simulation Result for the German Network Model

From the result of 20 searches on each sub-topology of the German network, a total of 110 paths were found between the specified nodes. Tables 3.1–3.4 in Appendix (A) show the detailed specification of the paths found in the German network sub-topologies.

Figure 6.18 shows the paths found from 20 searches in the different sub-topologies of the German network topology, namely the available capacity topology, the optimal available capacity topology and the trail topology. According to which at least three paths have been found between the specified source and destination nodes in every search. In 19 out of 20 searches, four of more paths were found either in the same topology or in a different sub-topology. And in 10 out of 20 searches at least 6 paths were found.


Figure 6.18 Number of paths found per-search per sub-topologies in the German network

As shown in Table 6.7 below, in 20 searches 15 paths were found in the German network trail sub-topology, 35 paths were found in the optimal available capacity sub-topology and 60 paths were found in the available capacity topology. Similarly, 7 searches for the paths between the specified source and destination nodes failed to find any path in the trail topology, 4 failed to find any path in the optimal available capacity sub-topology and no searches failed to find a path in the available capacity topology.

Table 6.7 Characteristics of the paths found in German Network sub-Topologies

| Topology | Total number of request | Path found | Path failed | Blocking rate | Total disjoint path found | Ration of disjoint /total |
|---|---|---|---|---|---|---|
| Trail topology | 20 | 15 | 7 | 0.35 | 13 | 0.65 |
| Optimal Available Capacity | 20 | 35 | 4 | 0.2 | | |
| Available Capacity | 20 | 60 | 0 | 0 | | |
| Total number of paths | | 110 | 11 | | | |

The algorithm inefficiency in the German network topology in terms of blocking rates and the ratio of disjoint paths to the total paths searched were calculated based on Equations (8) and (9), the results of which are shown in 6.7

As shown in the table above, 35% of searches in the trail sub-topology failed to find a path between the defined source and destination nodes. The ratio of failed paths to the total number of searches for the optimal available capacity sub-topology in the German network is 0.2, and it is 0 for the available capacity sub-topology, which means that one or more paths were found in every search for these sub-topologies in the German network model.

Figure 6.19 shows the changes in the total blocking rate at each sub-topology in the German network. According to which, as the blocking rate declines the number of paths found increases.

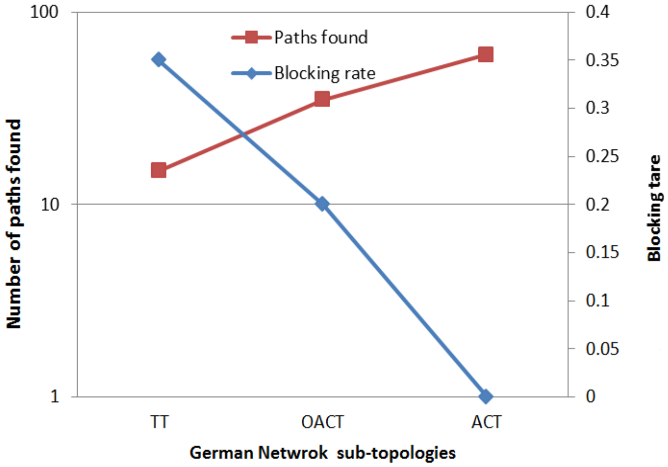



Figure 6.19 Number of path found and the blocking rates of three Sub- topologies of German network

The figure above exemplifies the three different sub-topologies of the German network model. As can be seen from the line shapes, the number of paths found increases as the blocking rate declines. It also suggests that the trail sub-topology (Tst) has the highest blocking rate, and consequently the least number of paths found for this sub-topology. The German network OAC sub-topology has the middle level of blocking rate at 0.2%, and consequently more paths than the Tst found in this sub-topology. The available capacity sub-topology shows the highest amount of paths found, as the blocking rate for this sub-topology is 0.

Table 6.8 shows the average path lengths and the average packet losses, considering the number of hops traversed by each path in the sub–topologies, namely TT, OACT and ACT. According to which the paths that traverse two hops to reach their destination node has an average length of 60 km, with average packet losses of 3%. In general, the data in Table 6.8 suggests that the average path length and the average packet losses increase as the number of hops increases.

Table 6.8 Average path lengths and average packet
(German network)

| Hopes | Average Length | Average packet losses |
|---|---|---|
| 2 | 60 | 3 |
| 3 | 78 | 3.9 |
| 4 | 107 | 5.35 |
| 5 | 124 | 6.2 |
| 6 | 126 | 6.3 |
| 7 | 130 | 6.5 |
| 8 | 145 | 7.25 |

Figure 6.20 which is based on data shown in the table above, suggests that as the number of hops traversed to reach the destination point increases, the path length increases. This phenomenon can be clearly seen in the figure below.

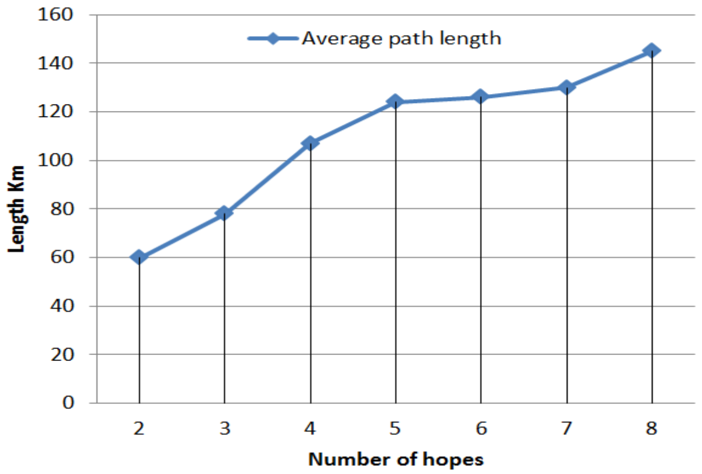



Figure 6.20 Average paths length found in the German network model

As we consider the packet losses to be proportional to the path length, so a similar shape is taken by the packet losses figure. Figure 6.21 shows the average path losses depending on the number of hops traversed for each path.

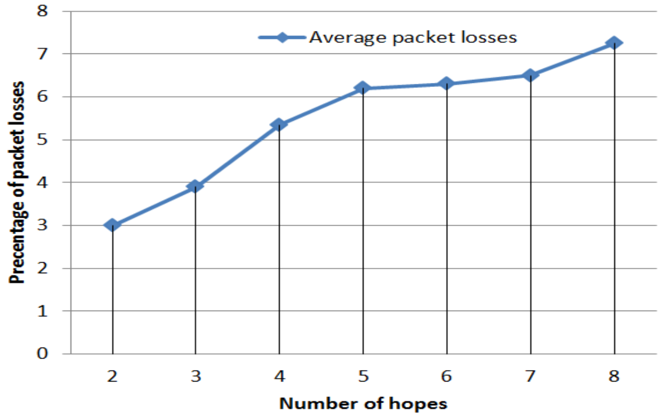



Figure 6.21 Average packet losses of the paths found in the German Network topology

As packet losses are assumed to be proportional to the paths length, this figure also shows the reduced percentage of the packet losses for paths with fewer nodes compared to paths with greater number of nodes.

The total number of paths found for each sub-topology, the disjoint paths selected and the path’s parameter are shown in Tables 3.1–3.4 in Appendix A.

## 6.10 Algorithm Performance Evaluation

In previous sub-sections of this chapter we applied the algorithm to US, European and German networks.

In order to evaluate the performance, in this sub-section we provide the combined results so as to control the algorithm's efficiency in terms of blocking rate on different sub-topologies and the ratio of disjoint path found to the total number of searches.

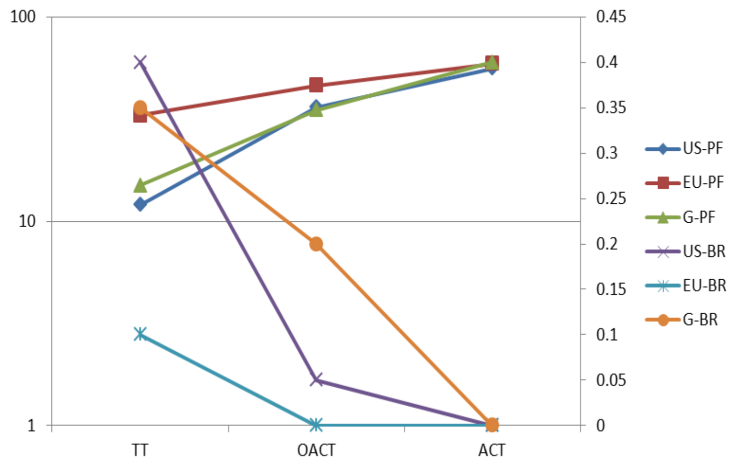



Figure 6.22 Number of paths found and blocking rates of three Sub- topologies of US, EU and German network

As can be seen from the figure above, in all three network models the algorithm performs well. As Figure 6.22 suggests, the algorithm found paths for every sub-topology of all three networks (three upper lines, US-PF, EU-PF, G-PF). In all three cases, fewer paths were found for the trail sub-topology than the OACT and the ACT. In the available capacity sub-topology, the maximum number of paths was found. Recalling our variables table, not all paths have an available trail. This means that by removing the links which do not have an available trail with sufficient capacity, the trail sub-topology's reachability declines. In contrast, all links in the available capacity sub-topology were included while searching for the paths. Obviously, the network's reachability is higher and obtaining more paths is more likely.

The blocking rates in all three networks decline as the topologies become more open. For instance, the blocking rate for the trail sub-topology is the highest. This is because in this sub-topology we have the lowest reachability of all three networks. But it is equal to zero for the available capacity topology since the network topology is maximally open.

In short, Figure 6.23 suggests that the algorithm fulfilled the requirement of finding paths for different layers and sub-topologies.

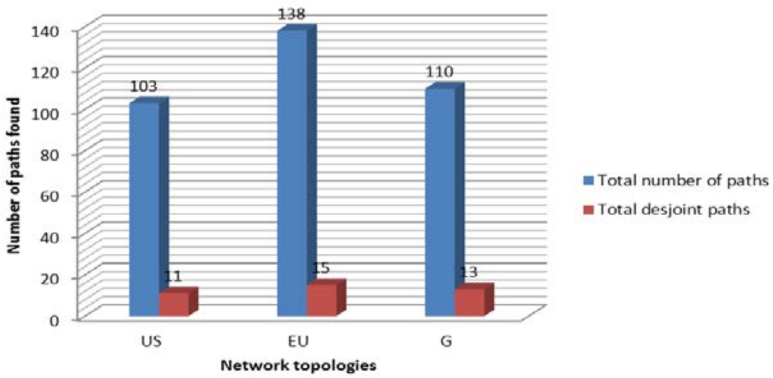



Figure 6.23 Total number of paths and total disjoint paths found in the US, EU and German network topologies

Similarly, Figure 6.23 suggests that the algorithm performs well in terms of finding all possible paths for specified source and destination nodes. As can also be seen from the figure above, in 20 searches 103 paths were found in the US network and 138 and 110 paths were found in the EU and German network topologies respectively.

This suggest that on average more than 5 paths were found per search in the US network topology, and 7 and 5.5 paths per search in the EU and German networks respectively.

Figure 6.23 proves that the algorithm fulfilled the second requirement, which is to find multiple paths for every specific source and destination node. Furthermore, Figure 6.26 suggests that in 11 out of 20 searches for the disjoint paths between the specified nodes, the request was successfully completed. In the EU network model, 75% of the requests were served in accordance to the user preferences, and 13 out of 20 requests were fulfilled in the German network model. This means that one of the main requirements of the network operators for finding a pair of disjoint paths between the specified source and destination nodes, with consideration of the user preferences, was also fulfilled by the algorithm proposed.

And finally, Tables 1.1-1.4, 2.1-2.4, and 3.1-3.4 (Appendix A) suggest that each path found has a different characteristic, such as packet loss, length, or delay. This allows the algorithm to try to address the user preferences.

## 6.11 Chapter Summary

Service provisioning is one of the main management tasks for today's transport and carrier network providers. Traditionally, the service provisioning process is manual, time consuming and costly. To provision a service, network operators have to consider the requested bandwidth, the required QoS, the available network resources, the non-desirable path identified by the user and the optimal network resource balanced usage. All the above-mentioned requirements need huge inventory evaluation, which may result in it taking a long time to come up with a concrete solution.

To allow more accurate, fast and economically efficient path computation, the Internet Engineering Task Force (IETF) introduced architecture for the Path Computation Element. Despite the introduction of the architecture, no standardized implementation exists for path computation.

The service provisioning problem has been studied by scholars, such as routing and wavelength assignment (RWA). They consider a network combining nodes connected by edges with an integer unit of capacity, and proposed heuristics to find paths between the nodes. While those kinds of heuristics perform well for networks with WDM technology, the approaches are not useful for the SDH/SONET network. This is because SDH/SONET imposes a specific multiplexing structure that needs to be taken into account when proposing a path computation solution. In this chapter we introduced a path computation algorithm which can address the specifics of SDH/SONET technology, as well as the requirement of the path computation provider as an enterprise entity. Furthermore, the algorithm is designed to return a pair of disjoint paths between the specified nodes, considering the user preferred path and the provider's priorities.

The current practices for finding a pair of disjoint path does not lead to the finding of an optimal path, as the removal of the first path found reduces the network's accessibility and consequently some of possible paths between the source and destination nodes cannot be found.

The approach followed in the algorithm allows the disjoint path to be optimal in terms of user preferences, as well as in terms of optimal possible path.

The algorithm efficiency in terms of blocking rates was tested on three different network topologies. Namely the US network topology, the EU network topology and the German network topology. Results show that algorithm fulfilled all three main goals. Namely, finding multi-layer paths, all possible paths between specific source and destination nodes, and paths with different characteristics called multi-option paths. Furthermore, the algorithm also fulfilled the requirement for an entropies PCE provider, which is the determination of a pair of disjoint paths considering the both the user and network provider's preferences and priorities.

The algorithm complexity is at the O[2n^2+n+3(V+E)] which is more complex than the K-shortest path implemented by Warshall, which is O[m+nlogn+k]. The complexity of the algorithm is based on BFS running 3 times and searching for paths on three different sub-topology graphs.

Concerning paths optimality, the proposed algorithm performs better than the similar algorithms. This is because; finding multi-constraint disjoint paths, is NP- complete. Practically, it is not possible to find a path fulfilling all QoS demanded by the user. The approaches such as the minimization of normalized sum of the constraint, for finding multi-constraint disjoint paths are far from the optimal solution.

As it is not possible to come up with an optimal solution considering all QoS parameters demanded, we consider the user preferences as the main constraint which must be satisfied. Furthermore, the disjoint paths search mechanism proposed in this chapter is far better than the current practices. This is because, in our approach the algorithm return a pair of disjoint path considering all possible path between the specified nodes as well as all possible disjoint paths between the two nodes.

The algorithm advantages over similar approaches are:

- The proposed algorithm allows path computation considering the SDH/SONET multiplexing structure.
- The algorithm returns a pair of disjoint paths which have the lowest sum of X (user preferences) among all pairs of disjoint paths between the source and destination nodes. This means that the pair of paths selected is the best optimal existing in the network, considering user preferences.
- The algorithm returns paths belonging to the three different sub-topology networks, which helps considering network operator's priorities.

# Chapter 7. Overall Summary and Policy Implications

## 7.1 Overall Summary

In this dissertation, we presented issues regarding the IP/MPLS network management system, and the transport layer network management system. The static nature of the transport network and interoperability issues does not allow the two layers to communicate automatically. Thus, a regular service/link provisioning process takes a long time and incurs high operational costs. Multiple solutions to the problem have been introduced by three groups of scholars, namely by the standardization organizations, by research support organizations and individual researchers. However, network operators are still looking for an easy to deploy, non-disruptive, and cost efficient solution.

We presented the IP/MPLS and transport network challenges in Chapter 1, and explained what motivated us to conduct this research. The chapter discusses the interoperability challenges currently facing IP/MPLS and transport networks. These interoperability issues have limited opportunity for automatic interaction and the coordination of network management functions.

In Chapter 2 we presented the efforts of other scholars with respect to the automation of the network management function. This chapter describes the efforts of the standardization organizations, which led to the introduction of the ASON/GMPLS control plane framework, the research support organization efforts which aimed to improve the already introduced GMPLS framework or to introduce new ways of addressing the problem, and the efforts of the telecommunication industry. We especially focus on the standardization organizations' efforts and the approach of the ONE project.

In Chapter 3 we presented a cost model to estimate the cost of migration to a new technology for a networks which is up and running. Furthermore, we presented and estimated the cost of GMPLS control plane deployment. Additionally we compared the service provisioning cost of a GMPLS enabled network with a traditional network. Techno-economic evaluations done in this chapter suggest that the challenge of GMPLS control plane deployment is rooted in technical and economic factors.

Chapter 4 describes our approach to the problem. In this chapter, we introduced a multi-input, multi-output mediator model. The proposed model architecture was designed to offer services for a “m” number of IP/MPLS, with their corresponding “n” number of transport providers. Our approach should be considered an extended version of the mediator model introduced by the ONE project.

Chapter 5 evaluates the impacts of the mediator model in the value creation activity of the Internet ecosystem. This chapter discusses the new business models enabled by the mediator model deployment. Findings of this chapter suggest that MM deployment will lead to a change in the value creation activities of the IP and transport layers. The results of our proposal also suggests that at least three new business models may emerge while deploying the MM in the Internet ecosystem.

Chapter 6 introduced an algorithm for path computation. The algorithm was presented and simulated, addressed the SDH/SONET technology requirements, as well as the requirements of an enterprise PCE provider. The simulation results suggest that the algorithm performs well. The algorithm proves it is efficiency by finding paths in different sub-topologies, and multiple paths for specified source and destination nodes with different characteristics. The most important advantage of proposed algorithm that it addresses the challenges of the current approaches for finding a pair of disjoint paths in the network.

## 7.2 Policy Implications

There are five main factors found that contribute to the GMPLS control plane low deployment rate. These are the GMPLS deployment cost, the GMPLS complexity, the GMPLS technical challenges, the GMPLS domain and layer dependency, and the traditional separation and isolation of the IP and transport networks working under the same administrative area.

### 7.2.1 Policy Implication to the Standardization Organizations

- The GMPLS technical challenges should be further studied and resolved so as to reduce its complexity of operation.
- With the fear of destabilizing the network, transport service providers are not willing to provide users the right to dynamically change bandwidth. Standardization organizations are required to ensure network stability by integrating new functionalities in control plane frameworks so as to encourage them to deploy new technology.
- The coordination of a network management function compared to the integration of a network management function was found to be cost effective and easy to deploy. So it would be better if standardization organizations also focus on the coordination approach as it can address the challenges not covered by the control plane framework.

### 7.2.2 Policy Implication to the TSPs

- The current separation between the IP and transport sections of the network is one of the reasons for the network's high operational cost. Network operators must reconsider their intra-organizational relationships (between the IP and transport sections of the network) so as to allow new services to be run over the network and to reduce operational costs by the coordination of network management functions.
- The current practices of computing a pair of disjoint paths between the specified nodes in the transport layer is costly, time consuming and error prone. As our study suggests, there are ways to address the requirements of transport service providers and automatically compute the path. Thus the support of transport network operators will help researchers to better understand their requirements and the challenges, in order to develop better solutions.

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**Appendix A.**

Table 1.1 Characteristics of the paths found in the NSF network sub-topologies

| Search number | S, D Nodes | Searched capacity | User Pref. | Path No | Tst | OACT | ACT | No-Hopes | P-Max. Capacity (VC12) | L (Km) | PL (%) | Path Delay (μc) | L/b | Disjoint paths selected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | (1-13) | 7Vc12 | Low cost | 1 | 1 | | | 3 | 300 | 130 | 4.4 | 715 | 0.37 | P7+P9=215 Km |
| | | | | 2 | | 1 | | 4 | 590 | 120 | 4 | 650 | 0.17 | |
| | | | | 3 | | 2 | | 5 | 590 | 125 | 4.4 | 715 | 0.19 | |
| | | | | 4 | | 3 | | 6 | 590 | 145 | 5.2 | 845 | 0.22 | |
| | | | | 5 | | 4 | | 6 | 590 | 150 | 5.6 | 910 | 0.24 | |
| | | | | 6 | | | 1 | 3 | 300 | 130 | 4.4 | 715 | 0.37 | |
| | | | | 7 | | | 2 | 4 | 280 | 105 | 4.4 | 715 | 0.39 | |
| | | | | 8 | | | 3 | 4 | 590 | 120 | 4 | 650 | 0.17 | |
| | | | | 9 | | | 4 | 5 | 300 | 110 | 4 | 650 | 0.33 | |
| | | | | 10 | | | 5 | 5 | 590 | 125 | 4.4 | 715 | 0.19 | |
| | | | | 11 | | | 6 | 5 | 590 | 140 | 5.2 | 845 | 0.22 | |
| | | | | 12 | | | 7 | 6 | 320 | 150 | 4 | 650 | 0.31 | |
| | | | | 13 | | | 8 | 6 | 300 | 100 | 5.6 | 910 | 0.47 | |
| | | | | 14 | | | 9 | 6 | 590 | 145 | 4.4 | 715 | 0.19 | |
| 2 | (2-13) | 10Vc12 | PL<=4% | 1 | 0 | | | | | | 0 | 0 | | Po2=2,3,6,11, 13 Pa4=2,8,10,13 |
| | | | | 2 | | 1 | | 4 | 590 | 100 | 4 | 650 | 0.17 | |
| | | | | 3 | | 2 | | 5 | 590 | 120 | 4.8 | 780 | 0.20 | |
| | | | | 4 | | | 1 | 3 | 280 | 90 | 3.6 | 585 | 0.32 | |
| | | | | 5 | | | 2 | 4 | 590 | 110 | 4.4 | 715 | 0.19 | |
| | | | | 6 | | | 3 | 5 | 590 | 120 | 4.8 | 780 | 0.20 | |
| 3 | (3-13) | 10Vc12 | Low cost | 1 | 0 | | | | | | 0 | 0 | | No disjoint Path available |
| | | | | 2 | | 1 | | 3 | 590 | 100 | 4 | 650 | 0.17 | |
| | | | | 3 | | 2 | | 4 | 590 | 100 | 4 | 650 | 0.17 | |
| | | | | 4 | | | 1 | 3 | 590 | 100 | 4 | 650 | 0.17 | |
| | | | | 5 | | | 2 | 4 | 590 | 100 | 4 | 650 | 0.17 | |
| 4 | (4-13) | 4Vc12 | De<700μs | 1 | 1 | | | 2 | 300 | 70 | 2.8 | 455 | 0.22 | Pt1=4,12,13 Pa4=4,5,7,810 ,13 |
| | | | | 2 | | | 1 | 2 | 300 | 70 | 2.8 | 455 | 0.23 | |
| | | | | 3 | | | 2 | 4 | 300 | 80 | 3.2 | 715 | 0.27 | |
| | | | | 4 | | | 3 | 5 | 300 | 80 | 3.2 | 650 | 0.27 | |
| | | | | 5 | | | 4 | 5 | 300 | 90 | 3.6 | 715 | 0.30 | |

(S,D)-Source, destination, (Tst)-Trail sub-topology, (OACT)-Optimal available capacity sub-topology, (ACT)-Available capacity sub-topology, (L)-Paths length, (PL)-Packet losses, (L/b)-Bandwidth normalized paths length

Table 1.2 Characteristics of the paths found in the NSF network sub-topologies

| Search number | S, D Nodes | Searched capacity | User Preferred path | Path No | Tst | OACT | ACT | No-Hopes | P-Max. Capacity (VC12) | L (Km) | PL (%) | Path Delay (μc) | L/b | Disjoint paths selected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | (5-13) | 8Vc12 | PL<=3,5% | 1 | | 1 | | 3 | 684 | 70 | 2.8 | 455 | 0.10 | Po1=5,6,11,13<br>Po2=5,7,8,10,13 |
| | | | | 2 | | 2 | | 4 | 320 | 80 | 3.2 | 520 | 0.25 | |
| | | | | 3 | | 3 | | 4 | 320 | 80 | 3.2 | 520 | 0.25 | |
| | | | | 4 | | | 1 | 3 | 684 | 70 | 2.8 | 455 | 0.10 | |
| | | | | 5 | | | 2 | 4 | 320 | 80 | 3.2 | 520 | 0.25 | |
| | | | | 6 | | | 3 | 4 | 320 | 80 | 3.2 | 520 | 0.25 | |
| 6 | (6-13) | 15Vc12 | De<=700μs | 1 | | 1 | | 2 | 684 | 60 | 2.4 | 390 | 0.09 | Po1=6,11,13<br>Po2=6,9,10,13 |
| | | | | 2 | | 2 | | 3 | 590 | 70 | 2.8 | 455 | 0.12 | |
| | | | | 3 | | | 1 | 2 | 684 | 60 | 2.4 | 390 | 0.09 | |
| | | | | 4 | | | 2 | 3 | 590 | 70 | 2.8 | 455 | 0.12 | |
| 7 | (7-13) | 3Vc12 | PL<=5% | 1 | 1 | | | 3 | 720 | 60 | 2.4 | 390 | 0.08 | No disjoint path available |
| | | | | 2 | | 1 | | 3 | 720 | 60 | 2.4 | 390 | 0.08 | |
| | | | | 3 | | 2 | | 3 | 720 | 60 | 2.4 | 390 | 0.08 | |
| | | | | 4 | | | 1 | 2 | 760 | 40 | 1.6 | 260 | 0.05 | |
| | | | | 5 | | | 2 | 2 | 760 | 40 | 1.6 | 260 | 0.05 | |
| 8 | (9-13) | Vc12 | Low cost | 1 | 1 | | | 2 | 320 | 30 | 3.2 | 195 | 0.09 | No disjoint path available |
| | | | | 2 | | 1 | | 2 | 590 | 30 | 1.2 | 195 | 0.05 | |
| | | | | 3 | | | 1 | 2 | 590 | 30 | 1.2 | 195 | 0.05 | |
| 9 | (1-14) | 7Vc12 | De<700μs | 1 | 1 | | | 3 | 900 | 120 | 3.2 | 650 | 0.38 | Po1=1,4,12,13<br>Pa9=1,3,6,11,13 |
| | | | | 2 | 2 | | | 5 | 730 | 130 | 3.3 | 845 | 0.43 | |
| | | | | 3 | | 1 | | 4 | 590 | 110 | 4.4 | 715 | 0.19 | |
| | | | | 4 | | 2 | | 5 | 590 | 120 | 4.8 | 780 | 0.20 | |
| | | | | 5 | | 3 | | 5 | 590 | 130 | 5.2 | 845 | 0.22 | |
| | | | | 6 | | 4 | | 6 | 590 | 140 | 5.6 | 910 | 0.24 | |
| | | | | 7 | | | 1 | 3 | 900 | 100 | 4 | 650 | 0.11 | |
| | | | | 8 | | | 2 | 4 | 280 | 110 | 4.4 | 715 | 0.39 | |
| | | | | 9 | | | 3 | 4 | 590 | 100 | 4 | 650 | 0.17 | |
| | | | | 10 | | | 4 | 5 | 590 | 110 | 4.4 | 715 | 0.19 | |
| | | | | 11 | | | 5 | 5 | 590 | 100 | 4 | 650 | 0.17 | |
| | | | | 12 | | | 6 | 6 | 320 | 110 | 4.4 | 715 | 0.34 | |
| | | | | 13 | | | 7 | 6 | 590 | 100 | 4 | 650 | 0.17 | |

Table 1.3 Characteristics of the paths found in the NSF network sub-topologies

| Search number | S, D Nodes | Searched capacity | User Pref. | Path No | Tst | OACT | ACT | No-Hopes | P-Max. Capacity (VC12) | L (Km) | PL (%) | Path Delay (µc) | L/b | Disjoint paths selected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | (4-14) | 10Vc12 | PL<5% | 1 | | 1 | | 2 | 950 | 80 | 3.2 | 520 | 0.08 | P1t=4,12,14<br>Po3=4,5,6,11,14 |
| | | | | 2 | | | 1 | 2 | 950 | 80 | 3.2 | 520 | 0.08 | |
| | | | | 3 | | | 2 | 4 | 300 | 80 | 3.2 | 520 | 0.27 | |
| | | | | 4 | | | 3 | 5 | 300 | 90 | 3.6 | 585 | 0.30 | |
| | | | | 5 | | | 4 | 5 | 300 | 80 | 3.2 | 520 | 0.27 | |
| 11 | (6-14) | 15Vc12 | De<500µs | 1 | 1 | | | 3 | 15 | 70 | 2.8 | 455 | 4.67 | Po2=6,11,14<br>Pt1=6,9,10,14 |
| | | | | 2 | | 1 | | 2 | 684 | 60 | 2.4 | 390 | 0.09 | |
| | | | | 3 | | 2 | | 3 | 590 | 70 | 2.8 | 455 | 0.12 | |
| | | | | 4 | | | 1 | 2 | 684 | 60 | 2.4 | 390 | 0.09 | |
| | | | | 5 | | | 2 | 3 | 590 | 70 | 2.8 | 455 | 0.12 | |
| 12 | (7-14) | 16 | PL<4,5% | 1 | 1 | | | 3 | 18 | 60 | 2.4 | 390 | 3.33 | No disjoint path available |
| | | | | 2 | | 1 | | 3 | 620 | 60 | 2.4 | 390 | 0.10 | |
| | | | | 3 | | | 1 | 3 | 620 | 60 | 2.4 | 390 | 0.10 | |
| 13 | (1-10) | 25Vc12 | De<=600µs | 1 | | 1 | | 4 | 590 | 90 | 3.6 | 585 | 0.15 | Po1=1,3,6,9,10<br>Po2=1,4,5,7,8,10 |
| | | | | 2 | | 2 | | 5 | 590 | 90 | 3.6 | 585 | 0.15 | |
| | | | | 3 | | | 1 | 3 | 280 | 100 | 4 | 650 | 0.36 | |
| | | | | 4 | | | 2 | 4 | 590 | 100 | 4 | 650 | 0.17 | |
| | | | | 5 | | | 3 | 5 | 590 | 90 | 3.6 | 585 | 0.15 | |
| | | | | 6 | | | 4 | 5 | 590 | 110 | 4.4 | 715 | 0.19 | |
| 14 | (2-11) | 6Vc12 | PL<3,5% | 1 | | 1 | | 3 | 590 | 100 | 4 | 650 | 0.17 | No disjoint path available |
| | | | | 2 | | | 1 | 3 | 590 | 100 | 4 | 650 | 0.17 | |
| 15 | (4-11) | 3Vc12 | Low cost | 3 | | | 1 | 3 | 300 | 70 | 2.8 | 455 | 0.23 | No disjoint path available |
| 15 | (2-9) | 7Vc12 | De<=500µs | 1 | 1 | | | 3 | 20 | 90 | 3.6 | 585 | 4.50 | No disjoint path available |
| | | | | 2 | | 1 | | 3 | 590 | 90 | 3.6 | 585 | 0.15 | |
| | | | | 3 | | | 1 | 3 | 590 | 90 | 3.6 | 585 | 0.15 | |

Table 1.4 Characteristics of the paths found in the NSF network sub-topologies

| Search number | S, D Nodes | Searched capacity | User Preferred path | Path No | Tst | OACT | ACT | No-Hopes | P-Max. Capacity (VC12) | L (Km) | PL (%) | Path Delay (µc) | L/b | Disjoint paths selected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 17 | (2-14) | 15Vc12 | Low cost | 1 | | 1 | | 4 | 590 | 110 | 4.4 | 715 | 0.19 | Po1=2,3,6,11,14<br>Pa3=2,8,14 |
| | | | | 2 | | 2 | | 5 | 590 | 120 | 4.8 | 780 | 0.20 | |
| | | | | 3 | | | 1 | 3 | 280 | 90 | 3.6 | 585 | 0.32 | |
| | | | | 4 | | | 2 | 4 | 590 | 110 | 4.4 | 715 | 0.19 | |
| | | | | 5 | | | 3 | 5 | 590 | 120 | 4.8 | 780 | 0.20 | |
| 18 | (3-14) | 3Vc12 | De<600µs | 1 | 1 | | | 4 | 18 | 100 | 4 | 650 | 5.56 | No disjoint path available |
| | | | | 2 | | 1 | | 3 | 590 | 90 | 3.6 | 585 | 0.15 | |
| | | | | 3 | | 2 | | 4 | 590 | 100 | 4 | 650 | 0.17 | |
| | | | | 4 | | | 1 | 3 | 590 | 90 | 3.6 | 585 | 0.15 | |
| | | | | 5 | | | 2 | 4 | 590 | 100 | 4 | 650 | 0.17 | |
| 19 | (5-14) | 25Vc12 | PL<3,5% | 1 | 1 | | | 4 | 12 | 80 | 3.2 | 520 | 6.67 | Pt1=5,7,8,10,14<br>Po1=5,6,11,14 |
| | | | | 2 | | 1 | | 3 | 684 | 70 | 2.8 | 455 | 0.10 | |
| | | | | 3 | | 2 | | 4 | 590 | 80 | 3.2 | 520 | 0.14 | |
| | | | | 4 | | 3 | | 4 | 590 | 70 | 2.8 | 455 | 0.12 | |
| | | | | 5 | | | 1 | 3 | 684 | 70 | 2.8 | 455 | 0.10 | |
| | | | | 6 | | | 2 | 4 | 320 | 70 | 2.8 | 455 | 0.22 | |
| | | | | 7 | | | 3 | 4 | 590 | 80 | 3.2 | 520 | 0.14 | |
| 20 | (8-13) | 3Vc12 | Low cost | | 1 | | | 2 | 840 | 40 | 1.6 | 260 | 0.05 | No disjoint path available |
| | | | | | | 1 | | 2 | 840 | 40 | 1.6 | 260 | 0.05 | |
| | | | | | | | 1 | 2 | 840 | 40 | 1.6 | 260 | 0.05 | |

Table 1.5 Number of the paths found in the NSF network sub-topologies

| Search number | Number of paths found in the TT | Number of paths found in the OACT | Number of paths found in the ACT | Disjoint pairs |
|---|---|---|---|---|
| **1** | 1 | 2 | 3 | 2 |
| **2** | 0 | 1 | 2 | 1 |
| **3** | 0 | 2 | 2 | 0 |
| **4** | 1 | 0 | 3 | 2 |
| **5** | 1 | 3 | 3 | 2 |
| **6** | 0 | 2 | 2 | 2 |
| **7** | 1 | 1 | 1 | 0 |
| **8** | 0 | 1 | 1 | 0 |
| **9** | 1 | 1 | 1 | 0 |
| **10** | 2 | 3 | 3 | 2 |
| **11** | 0 | 1 | 2 | 1 |
| **12** | 1 | 2 | 2 | 0 |
| **13** | 1 | 2 | 3 | 2 |
| **14** | 0 | 1 | 3 | 2 |
| **15** | 1 | 2 | 2 | 2 |
| **16** | 1 | 1 | 1 | 0 |
| **17** | 0 | 2 | 3 | 2 |
| **18** | 0 | 1 | 1 | 0 |
| **19** | 0 | 0 | 1 | 0 |
| **20** | 1 | 1 | 1 | 0 |
| **Total** | 12 | 29 | 40 | 20 |

Table 2.1 Characteristics of the paths found in the EU network sub-topologies

| Search number | S, D Nodes | Searched capacity | User Preferred | Paths No | Tst | OACT | ACT | No-Hopes | P-Max. Capacity (VC12) | Paths length (Km) | Packet Losses (%) | Paths Delay (μc) | B/L | Disjoint Paths selected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | (1-19) | 5Vc12 | De<400μs | 1 | 1 | | | 4 | 620 | 50 | 2 | 325 | 0.08 | P1t=1,4,7,10,19 Pt5=1,2,3,6,9,19 |
| | | | | 2 | 2 | | | 4 | 590 | 50 | 2 | 325 | 0.08 | |
| | | | | 3 | 3 | | | 5 | 590 | 60 | 2.4 | 390 | 0.10 | |
| | | | | 4 | 4 | | | 5 | 320 | 60 | 2.4 | 390 | 0.19 | |
| | | | | 5 | 5 | | | 5 | 590 | 60 | 2.4 | 390 | 0.10 | |
| | | | | 6 | 6 | | | 5 | 320 | 60 | 2.4 | 390 | 0.19 | |
| | | | | 7 | 7 | | | 7 | 320 | 70 | 2.8 | 455 | 0.22 | |
| | | | | 8 | | 1 | | 4 | 590 | 50 | 2 | 325 | 0.08 | |
| | | | | 9 | | 2 | | 5 | 320 | 60 | 2.4 | 390 | 0.19 | |
| | | | | 10 | | 3 | | 5 | 590 | 60 | 2.4 | 390 | 0.10 | |
| | | | | 11 | | | 1 | 4 | 620 | 50 | 2 | 325 | 0.08 | |
| | | | | 12 | | | 2 | 4 | 590 | 50 | 2 | 325 | 0.08 | |
| | | | | 13 | | | 3 | 5 | 590 | 60 | 2.4 | 390 | 0.10 | |
| | | | | 14 | | | 4 | 5 | 320 | 60 | 2.4 | 390 | 0.19 | |
| | | | | 15 | | | 5 | 5 | 590 | 60 | 2.4 | 390 | 0.10 | |
| | | | | 16 | | | 6 | 5 | 320 | 60 | 2.4 | 390 | 0.19 | |
| | | | | 17 | | | 7 | 7 | 320 | 70 | 2.8 | 455 | 0.22 | |
| 2 | (12-21) | 4Vc12 | PL<4% | 1 | 1 | | | 7 | 320 | 110 | 4.4 | 715 | 0.34 | No disjoint path found |
| | | | | 2 | 2 | | | 5 | 320 | 40 | 1.6 | 260 | 0.13 | |
| | | | | 3 | 3 | | | 5 | 320 | 50 | 2 | 325 | 0.16 | |
| | | | | 4 | | 1 | | 7 | 320 | 110 | 4.4 | 715 | 0.34 | |
| | | | | 5 | | 2 | | 5 | 320 | 40 | 1.6 | 260 | 0.13 | |
| | | | | 6 | | 3 | | 5 | 320 | 50 | 2 | 325 | 0.16 | |
| | | | | 7 | | 4 | | 8 | 320 | 80 | 3.2 | 520 | 0.25 | |
| | | | | 8 | | 5 | | 6 | 320 | 60 | 2.4 | 390 | 0.19 | |
| | | | | 9 | | | 1 | 7 | 320 | 110 | 4.4 | 715 | 0.34 | |
| | | | | 10 | | | 2 | 5 | 320 | 40 | 1.6 | 260 | 0.13 | |
| | | | | 11 | | | 3 | 5 | 320 | 50 | 2 | 325 | 0.16 | |
| | | | | 12 | | | 4 | 8 | 320 | 80 | 3.2 | 520 | 0.25 | |
| | | | | 13 | | | 5 | 6 | 320 | 60 | 2.4 | 390 | 0.19 | |

(S,D)-Source, destination, (Tst)-Trail sub-topology, (OACT)-Optimal available capacity sub-topology, (ACT)-Available capacity sub-topology, (L)-Paths length, (PL)-Packet losses, (L/b)-Bandwidth normalized paths length

Table 2.2  Characteristics of the paths found in the EU network sub-topologies

| Search number | S, D Nodes | Searched capacity | User Preferred | Paths No | Tst | OACT | ACT | No-Hopes | P-Max. Capacity (VC12) | Paths length (Km) | Packet Losses (%) | Paths Delay (µc) | B/L | Disjoint Paths selected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | (8-19) | 10Vc12 | PL<3% | 1 | 1 | | | 3 | 620 | 30 | 1.2 | 195 | 0.05 | Pt1=8,5,9,19 Pt2=8,17,16,20, 18,21,19 |
| | | | | 2 | 2 | | | 6 | 320 | 60 | 2.4 | 390 | 0.19 | |
| | | | | 3 | | 1 | | 3 | 620 | 30 | 1.2 | 195 | 0.05 | |
| | | | | 4 | | 2 | | 6 | 320 | 60 | 2.4 | 390 | 0.19 | |
| | | | | 5 | | 3 | | 5 | 320 | 50 | 2 | 325 | 0.16 | |
| | | | | 6 | | 4 | | 8 | 320 | 80 | 3.2 | 520 | 0.25 | |
| | | | | 7 | | | 1 | 3 | 620 | 30 | 1.2 | 195 | 0.05 | |
| | | | | 8 | | | 2 | 6 | 320 | 60 | 2.4 | 390 | 0.19 | |
| | | | | 9 | | | 3 | 5 | 320 | 50 | 2 | 325 | 0.16 | |
| | | | | 10 | | | 4 | 8 | 320 | 80 | 3.2 | 520 | 0.25 | |
| 4 | (4-11) | 15Vc12 | De<300µs | 1 | 1 | | | 2 | 590 | 20 | 0.8 | 130 | 0.03 | Pt1=4,7,11 Po2=4,3,6,10,19,11 |
| | | | | 2 | | 1 | | 2 | 590 | 20 | 0.8 | 130 | 0.03 | |
| | | | | 3 | | 2 | | 5 | 590 | 50 | 2 | 325 | 0.08 | |
| | | | | 4 | | 3 | | 5 | 320 | 50 | 2 | 325 | 0.16 | |
| | | | | 5 | | 4 | | 7 | 320 | 70 | 2.8 | 455 | 0.22 | |
| | | | | 6 | | | 1 | 2 | 590 | 20 | 0.8 | 130 | 0.03 | |
| | | | | 7 | | | 2 | 5 | 590 | 50 | 2 | 325 | 0.08 | |
| | | | | 8 | | | 3 | 5 | 320 | 50 | 2 | 325 | 0.16 | |
| | | | | 9 | | | 4 | 7 | 320 | 70 | 2.8 | 455 | 0.22 | |
| 5 | (2-9) | 8Vc12 | De<600µs | 1 | 1 | | | 3 | 320 | 30 | 1.2 | 195 | 0.09 | Pt1=2,3,6,9 Po1=2,5,9 |
| | | | | 2 | | 1 | | 2 | 800 | 20 | 0.8 | 130 | 0.03 | |
| | | | | 3 | | 2 | | 3 | 320 | 30 | 1.2 | 195 | 0.09 | |
| | | | | 4 | | | 1 | 2 | 800 | 20 | 0.8 | 130 | 0.03 | |
| | | | | 5 | | | 2 | 3 | 320 | 30 | 1.2 | 195 | 0.09 | |
| 6 | (16-24) | 20Vc12 | PL<3,5% | 1 | 1 | | | 3 | 590 | 30 | 1.2 | 195 | 0.05 | Pt1=16,22,23,24 Po3=16,20,18,21, 25,24 |
| | | | | 2 | | 1 | | 3 | 590 | 30 | 1.2 | 195 | 0.05 | |
| | | | | 3 | | 2 | | 5 | 320 | 50 | 2 | 325 | 0.16 | |
| | | | | 4 | | 3 | | 7 | 320 | 70 | 2.8 | 455 | 0.22 | |
| | | | | 5 | | | 1 | 3 | 590 | 30 | 1.2 | 195 | 0.05 | |
| | | | | 6 | | | 2 | 5 | 320 | 50 | 2 | 325 | 0.16 | |
| | | | | 7 | | | 3 | 7 | 320 | 70 | 2.8 | 455 | 0.05 | |

Table 2.3 Characteristics of the paths found in the EU network sub-topologies

| Search number | S, D Nodes | Searched capacity | User Preferred | Paths No | Tst | OACT | ACT | No-Hopes | P-Max. Capacity (VC12) | Paths length (Km) | Packet Losses (%) | Paths Delay (μc) | B/L | Disjoint Paths selected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | (7-28) | 3Vc12 | De<400μs | 1 | 1 | | | 2 | 720 | 20 | 0.8 | 130 | 0.03 | Pt1=7,11,28 Pa9=7,10,19,26 ,27,28 |
| | | | | 2 | 2 | | | 4 | 684 | 40 | 1.6 | 260 | 0.06 | |
| | | | | 3 | | 1 | | 2 | 720 | 20 | 0.8 | 130 | 0.03 | |
| | | | | 4 | | 2 | | 4 | 684 | 40 | 1.6 | 260 | 0.06 | |
| | | | | 6 | | 3 | | 5 | 400 | 50 | 2 | 325 | 0.13 | |
| | | | | 7 | | | 1 | 2 | 720 | 20 | 0.8 | 130 | 0.03 | |
| | | | | 8 | | | 2 | 4 | 684 | 40 | 1.6 | 260 | 0.06 | |
| | | | | 9 | | | 3 | 5 | 400 | 50 | 2 | 325 | 0.13 | |
| 8 | (16-25) | 13Vc12 | PL<=5% | 1 | 1 | | | 2 | 590 | 20 | 0.8 | 130 | 0.03 | Pt1=16,22,25 Pt2=16,20,18, 21,25 |
| | | | | 2 | 2 | | | 4 | 320 | 40 | 1.6 | 260 | 0.13 | |
| | | | | 3 | | 1 | | 2 | 590 | 20 | 0.8 | 130 | 0.03 | |
| | | | | 4 | | 2 | | 4 | 320 | 40 | 1.6 | 260 | 0.13 | |
| | | | | 5 | | 3 | | 7 | 320 | 70 | 2.8 | 455 | 0.22 | |
| | | | | 6 | | | 1 | 2 | 590 | 20 | 0.8 | 130 | 0.03 | |
| | | | | 7 | | | 2 | 4 | 320 | 40 | 1.6 | 260 | 0.13 | |
| | | | | 8 | | | 3 | 7 | 320 | 70 | 2.8 | 455 | 0.22 | |
| 9 | (8-20) | 9Vc12 | Low cost (Shortest distance) | 1 | 1 | | | 3 | 590 | 30 | 1.2 | 195 | 0.05 | Pt1=8,17,16,20 Pa4=8,5,9,18,21, 25,20 |
| | | | | 2 | | 1 | | 3 | 590 | 30 | 1.2 | 195 | 0.05 | |
| | | | | 3 | | | 1 | 3 | 590 | 30 | 1.2 | 195 | 0.05 | |
| | | | | 4 | | | 2 | 6 | 320 | 60 | 2.4 | 390 | 0.19 | |
| 10 | (1-10) | 20Vc12 | De<500μs | 1 | 1 | | | 3 | 590 | 40 | 1.6 | 260 | 0.07 | Pt1=1,4,7,10 Pt2=1,2,3,6,10 |
| | | | | 2 | 2 | | | 4 | 590 | 50 | 2 | 325 | 0.08 | |
| | | | | 3 | | 1 | | 3 | 590 | 40 | 1.6 | 260 | 0.07 | |
| | | | | 4 | | 2 | | 4 | 590 | 50 | 2 | 325 | 0.08 | |
| | | | | 5 | | | 1 | 3 | 590 | 40 | 1.6 | 260 | 0.07 | |
| | | | | 6 | | | 2 | 4 | 590 | 50 | 2 | 325 | 0.08 | |
| | | | | 7 | | | 3 | 4 | 590 | 50 | 2 | 325 | 0.08 | |

Table 2.4 Characteristics of the paths found in the EU network sub-topologies

| Search number | S, D Nodes | Searched capacity | User Preferred | Paths No | Tst | OACT | ACT | No-Hopes | P-Max. Capacity (VC12) | Paths length (Km) | Packet Losses (%) | Paths Delay (µc) | B/L | Disjoint Paths selected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11 | (21-28) | 3Vc12 | De<600µs | 1 | | 1 | | 3 | 760 | 30 | 1.2 | 195 | 0.04 | Po1=21,19,11,28 Pa4=21,19,26, 27,28 |
| | | | | 3 | | | 1 | 3 | 760 | 30 | 1.2 | 195 | 0.04 | |
| | | | | 4 | | | 2 | 4 | 400 | 40 | 1.6 | 260 | 0.10 | |
| | | | | 6 | | | 3 | 11 | 400 | 110 | 4.4 | 715 | 0.28 | |
| | | | | 7 | | | 4 | 12 | 300 | 120 | 4.8 | 780 | 0.40 | |
| 12 | (15-17) | 16Vc12 | PL<5% | 1 | 1 | | | 4 | 320 | 50 | 2 | 325 | 0.16 | No disjoint path available |
| | | | | 2 | | 1 | | 4 | 320 | 50 | 2 | 325 | 0.16 | |
| | | | | 3 | | 2 | | 4 | 320 | 40 | 1.6 | 260 | 0.13 | |
| | | | | 4 | | | 1 | 4 | 320 | 50 | 2 | 325 | 0.16 | |
| | | | | 5 | | | 2 | 4 | 320 | 40 | 1.6 | 260 | 0.13 | |
| 13 | (6-19) | 2Vc12 | De<400µs | 1 | 1 | | | 2 | 320 | 20 | 0.8 | 130 | 0.06 | Pt1=6,10,19 Pt2=6,919 |
| | | | | 2 | 2 | | | 2 | 730 | 20 | 0.8 | 130 | 0.03 | |
| | | | | 3 | | 1 | | 2 | 320 | 20 | 0.8 | 130 | 0.06 | |
| | | | | 4 | | 2 | 1 | 2 | 730 | 20 | 0.8 | 130 | 0.03 | |
| | | | | 5 | | | 2 | 2 | 320 | 20 | 0.8 | 130 | 0.06 | |
| | | | | 6 | | | | 2 | 730 | 20 | 0.8 | 130 | 0.03 | |
| 14 | (13-16) | 20Vc12 | De<500µs | 1 | 1 | | | 3 | 590 | 60 | 2.4 | 390 | 0.10 | No disjoint path available |
| | | | | 2 | | 1 | | 3 | 590 | 60 | 2.4 | 390 | 0.10 | |
| | | | | 3 | | | 1 | 3 | 590 | 60 | 2.4 | 390 | 0.10 | |
| 15 | (7-27) | 6Vc12 | PL<=4% | 1 | 1 | | | 4 | 684 | 40 | 1.6 | 260 | 0.06 | No disjoint path available |
| | | | | 2 | | 1 | | 4 | 684 | 40 | 1.6 | 260 | 0.06 | |
| | | | | 3 | | | 1 | 4 | 684 | 40 | 1.6 | 260 | 0.06 | |
| 16 | (8-11) | Vc12 | De<500µs | 1 | 1 | | | 4 | 620 | 40 | 1.6 | 260 | 0.06 | Pt1=8,5,9,19,11 Pt2=8,17,16,20, 18,21,19,11 |
| | | | | 2 | 2 | | | 7 | 320 | 70 | 2.8 | 455 | 0.22 | |
| | | | | 3 | | 1 | | 4 | 620 | 40 | 1.6 | 260 | 0.06 | |
| | | | | 4 | | 2 | | 7 | 320 | 70 | 2.8 | 455 | 0.22 | |
| | | | | 5 | | | 1 | 4 | 620 | 40 | 1.6 | 260 | 0.06 | |
| | | | | 6 | | | 2 | 7 | 320 | 70 | 2.8 | 455 | 0.22 | |

Table 2.5 Characteristics of the paths found in the EU network sub-topologies

| Search number | S, D Nodes | Searched capacity | User Preferred | Paths No | Tst | OACT | ACT | No-Hopes | P-Max. Capacity (VC12) | Paths length (Km) | Packet Losses (%) | Paths Delay (µc) | B/L | Disjoint Paths selected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 17 | (9-28) | 5Vc12 | De<500µs | 1 | 1 | | | 3 | 620 | 30 | 1.2 | 195 | 0.05 | Pt1=9,19,11,28 Pa8=9,18,,21,19, 26,27,28 |
| | | | | 2 | | 1 | | 3 | 620 | 30 | 1.2 | 195 | 0.05 | |
| | | | | 3 | | 2 | | 4 | 300 | 40 | 1.6 | 260 | 0.13 | |
| | | | | 4 | | | 1 | 3 | 620 | 30 | 1.2 | 195 | 0.05 | |
| | | | | 6 | | | 2 | 3 | 620 | 30 | 1.2 | 195 | 0.05 | |
| | | | | 7 | | | 3 | 4 | 300 | 40 | 1.6 | 260 | 0.13 | |
| | | | | 8 | | | 4 | 6 | 300 | 60 | 2.4 | 390 | 0.20 | |
| 18 | (9-19) | 30Vc12 | De<=600µs | 1 | 1 | | | 1 | 620 | 10 | 0.4 | 65 | 0.02 | Pt1=9,19 Pa5=9,18,21,19 |
| | | | | 2 | | 1 | | 1 | 620 | 10 | 0.4 | 65 | 0.02 | |
| | | | | 3 | | 2 | | 3 | 320 | 30 | 1.2 | 195 | 0.09 | |
| | | | | 4 | | | 1 | 1 | 620 | 10 | 0.4 | 65 | 0.02 | |
| | | | | 5 | | | 2 | 3 | 320 | 30 | 1.2 | 195 | 0.09 | |
| 19 | (16-17) | 8Vc12 | PL<4,5% | 1 | 1 | | | 3 | 500 | 30 | 1.2 | 195 | 0.06 | Pt1=16,12,8,17 Pa6=16,20,18,17 |
| | | | | 2 | | 1 | | 3 | 500 | 30 | 1.2 | 195 | 0.06 | |
| | | | | 3 | | 2 | | 3 | 590 | 30 | 1.2 | 195 | 0.05 | |
| | | | | 4 | | | 1 | 3 | 500 | 30 | 1.2 | 195 | 0.06 | |
| | | | | 5 | | | 2 | 3 | 590 | 30 | 1.2 | 195 | 0.05 | |
| | | | | 6 | | | 3 | 5 | 300 | 50 | 2 | 325 | 0.17 | |
| 20 | (1-14) | 15Vc12 | PL<5% | 1 | | 1 | | 9 | 340 | 120 | 4.8 | 780 | 0.35 | No disjoint path available |
| | | | | 2 | | | 1 | 9 | 340 | 120 | 4.8 | 780 | 0.35 | |
| | | | | 3 | | | 2 | 10 | 600 | 140 | 5.6 | 910 | 0.23 | |

Table 2.6 Number of the paths found in the NSF network sub-topologies

| Search number | Number of paths found in the TT | Number of paths found in the OACT | Number of paths found in the ACT | Disjoint pairs |
|---|---|---|---|---|
| 1 | 7 | 3 | 7 | 1 |
| 2 | 3 | 5 | 5 | 0 |
| 3 | 2 | 4 | 4 | 1 |
| 4 | 1 | 4 | 4 | 1 |
| 5 | 1 | 2 | 2 | 1 |
| 6 | 1 | 3 | 3 | 1 |
| 7 | 2 | 3 | 3 | 1 |
| 8 | 2 | 3 | 3 | 1 |
| 9 | 1 | 1 | 2 | 1 |
| 10 | 2 | 2 | 3 | 1 |
| 11 | 0 | 1 | 4 | 1 |
| 12 | 1 | 2 | 2 | 0 |
| 13 | 2 | 2 | 2 | 1 |
| 14 | 1 | 1 | 1 | 0 |
| 15 | 1 | 1 | 1 | 0 |
| 16 | 2 | 2 | 2 | 1 |
| 17 | 1 | 2 | 4 | 1 |
| 18 | 1 | 2 | 2 | 1 |
| 19 | 1 | 2 | 3 | 1 |
| 20 | 0 | 1 | 2 | 0 |
| Total | 33 | 46 | 59 | 15 |

Table 3.1 Characteristics of the paths found in the German network sub-topologies

| Search number | S, D Nodes | Searched capacity | User Preferred | Path No | Tst | OACT | ACT | No-Hops | P-Max. Capacity (VC12) | Paths Length (Km) | Paths Loses (%) | Paths Delay (µs) | L/b | Disjoint Paths selected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | (7-16) | 15Vc12 | Nh<6 | 1 | 1 | | | 4 | 720 | 100 | 4 | 650 | 0.139 | Pt1=7,8,12,13,16 Po4=7,9,14,13,15,16 |
| | | | | 2 | | 1 | | 4 | 720 | 130 | 5.2 | 845 | 0.181 | |
| | | | | 3 | | 2 | | 4 | 684 | 140 | 5.6 | 910 | 0.205 | |
| | | | | 4 | | 3 | | 5 | 500 | 150 | 6 | 975 | 0.030 | |
| | | | | 5 | | | 1 | 4 | 720 | 130 | 5.2 | 845 | 0.181 | |
| | | | | 6 | | | 2 | 4 | 684 | 140 | 5.6 | 910 | 0.205 | |
| | | | | 7 | | | 3 | 5 | 500 | 150 | 6 | 975 | 0.300 | |
| 2 | (7-16) | Vc12 | De<1 µs | 1 | 1 | | | 4 | 720 | 130 | 5.2 | 845 | 0.181 | Pt1=7,8,12,13,16 Po6=7,9,14,13,15,16 |
| | | | | 2 | 2 | | | 4 | 684 | 140 | 5.6 | 910 | 0.205 | |
| | | | | 3 | 3 | | | 5 | 500 | 150 | 6 | 975 | 0.300 | |
| | | | | 4 | | 1 | | 4 | 720 | 130 | 5.2 | 845 | 0.181 | |
| | | | | 5 | | 2 | | 4 | 684 | 140 | 5.6 | 910 | 0.205 | |
| | | | | 6 | | 3 | | 5 | 500 | 150 | 6 | 975 | 0.300 | |
| | | | | 7 | | | 1 | 4 | 720 | 130 | 5.2 | 845 | 0.181 | |
| | | | | 8 | | | 2 | 4 | 684 | 140 | 5.6 | 910 | 0.205 | |
| | | | | 9 | | | 3 | 5 | 500 | 150 | 6 | 975 | 0.300 | |
| 3 | (15-12) | 4Vc12 | De<800µs | 1 | 1 | | | 3 | 280 | 70 | 2.8 | 455 | 0.250 | Pt1=15,16,17,12 Po3=15,14,13,7,8,12 |
| | | | | 2 | | 1 | | 3 | 280 | 70 | 2.8 | 455 | 0.250 | |
| | | | | 3 | | 2 | | 5 | 500 | 120 | 4.8 | 780 | 0.240 | |
| | | | | 4 | | 3 | | 5 | 280 | 120 | 4.8 | 780 | 0.429 | |
| | | | | 5 | | | 1 | 3 | 280 | 70 | 2.8 | 455 | 0.250 | |
| | | | | 6 | | | 2 | 5 | 500 | 120 | 4.8 | 780 | 0.240 | |
| | | | | 7 | | | 3 | 5 | 280 | 120 | 4.8 | 780 | 0.429 | |
| 4 | (15-12) | 40Vc12 | PL<5% | 1 | | 1 | | 5 | 500 | 120 | 4.8 | 780 | 0.240 | Po1=15,14,13,7,8,12 Po4=15,16,17,12 |
| | | | | 2 | | | 1 | 3 | 280 | 70 | 2.8 | 455 | 0.250 | |
| | | | | 3 | | | 2 | 5 | 500 | 120 | 4.8 | 780 | 0.240 | |
| | | | | 4 | | | 3 | 5 | 280 | 120 | 4.8 | 780 | 0.429 | |

(S,D)-Source, destination, (Tst)-Trail sub-topology, (OACT)-Optimal available capacity sub-topology, (ACT)-Available capacity sub-topology, (L)-Paths length, (PL)-Packet losses, (L/b)-Bandwidth normalized paths length

Table 3.2 Characteristics of the paths found in the German network sub-topologies

| Search number | S, D Nodes | Searched capacity | User Preferred | Path No | Tst | OACT | ACT | No-Hops | P-Max. Capacity (VC12) | Paths Length (Km) | Paths Loses (%) | Paths Delay (µs) | L/b | Disjoint Paths selected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | (12-9) | 45Vc12 | De<600µs | 1 | 1 | | | 3 | 684 | 90 | 3.6 | 585 | 0.132 | No disjoint paths available |
| | | | | 2 | | 1 | | 2 | 620 | 60 | 2.4 | 390 | 0.097 | |
| | | | | 3 | | 2 | | 3 | 684 | 90 | 3.6 | 585 | 0.132 | |
| | | | | 4 | | | 1 | 2 | 684 | 60 | 2.4 | 390 | 0.088 | |
| | | | | 5 | | | 2 | 3 | 620 | 90 | 3.6 | 585 | 0.145 | |
| | | | | 6 | | | 3 | 4 | 684 | 120 | 4.8 | 780 | 0.175 | |
| 6 | (15-8) | 6Vc12 | PL<5% | 1 | | 0 | | | | | | | 0 | Pa2=15,14,13,7,8<br>Pa3=15,16,17,12,11,10,8 |
| | | | | 2 | | | 1 | 4 | 280 | 120 | 4.8 | 780 | 0.429 | |
| | | | | 3 | | | 2 | 6 | 500 | 100 | 4 | 650 | 0.200 | |
| | | | | 4 | | | 3 | 7 | 280 | 160 | 6.4 | 1040 | 0.571 | |
| 7 | (15-8) | 1Vc12 | PL<5% | 1 | 1 | | | 6 | 280 | 100 | 4 | 650 | 0.357 | Pt1=15,16,17,12,11,10,8<br>Pa2=15,14,13,7,8 |
| | | | | 2 | | 1 | | 4 | 500 | 110 | 4.4 | 715 | 0.220 | |
| | | | | 3 | | 2 | | 4 | 280 | 120 | 4.8 | 780 | 0.429 | |
| | | | | 4 | | 3 | | 8 | 280 | 160 | 6.4 | 1040 | 0.571 | |
| | | | | 5 | | | 1 | 6 | 280 | 100 | 4 | 650 | 0.357 | |
| | | | | 6 | | | 2 | 4 | 500 | 110 | 4.4 | 715 | 0.220 | |
| | | | | 7 | | | 3 | 4 | 280 | 120 | 4.8 | 780 | 0.429 | |
| | | | | 8 | | | 4 | 8 | 280 | 160 | 6.4 | 1040 | 0.571 | |
| 8 | (7-16) | 4Vc12 | De<600µs | 1 | 1 | | | 4 | 720 | 90 | 3.6 | 585 | 0.125 | Pt1=7,8,12,13,16<br>Po2=7,9,14,13,16 |
| | | | | 2 | | 1 | | 4 | 720 | 90 | 3.6 | 585 | 0.125 | |
| | | | | 3 | | 2 | | 4 | 684 | 120 | 4.8 | 780 | 0.175 | |
| | | | | 4 | | 3 | | 5 | 500 | 130 | 5.2 | 845 | 0.260 | |
| | | | | 5 | | | 1 | 4 | 720 | 90 | 3.6 | 585 | 0.125 | |
| | | | | 6 | | | 2 | 4 | 684 | 120 | 4.8 | 780 | 0.175 | |
| | | | | 7 | | | 3 | 5 | 500 | 130 | 5.2 | 845 | 0.260 | |
| 9 | (13-8) | 23Vc12 | PL<4% | 1 | | 1 | | 2 | 700 | 60 | 2.4 | 390 | 0.086 | Po1=13,7,8<br>Pa3=13,16,17,12,11,10,8 |
| | | | | 2 | | | 1 | 2 | 700 | 60 | 2.4 | 390 | 0.086 | |
| | | | | 3 | | | 2 | 6 | 500 | 100 | 4 | 650 | 0.200 | |
| | | | | 4 | | | 3 | 7 | 280 | 120 | 4.8 | 780 | 0.429 | |
| 10 | (13-3) | 10Vc12 | De<700µs | 1 | | 1 | | 3 | 320 | 80 | 3.2 | 520 | 0.132 | No disjoint paths available |
| | | | | 2 | | | 1 | 3 | 320 | 80 | 3.2 | 520 | 0.097 | |
| | | | | 3 | | | 2 | 5 | 320 | 100 | 4 | 650 | 0.132 | |

Table 3.3 Characteristics of the paths found in the German network sub-topologies

| Search number | S, D Nodes | Searched capacity | User Preferred | Path No | Tst | OACT | ACT | No-Hops | P-Max. Capacity (VC12) | Paths Length (Km) | Paths Loses (%) | Paths Delay (µs) | L/b | Disjoint Paths selected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11 | (13-1) | 8Vc12 | Low cost | 1 | | | 1 | 3 | 280 | 80 | 3.2 | 520 | 0.286 | Pa1=13,7,4,1 |
| | | | | 2 | | | 2 | 8 | 300 | 150 | 6 | 975 | 0.500 | Pa2=1,2,3,6,7,8,12,13 |
| 12 | (4-12) | 2Vc12 | PL<5% | 1 | 1 | | | 6 | 300 | 120 | 4.8 | 780 | 0.400 | Pt1=4,3,5,6,7,8,12<br>Pa3=4,9,14,13,16,17,12 |
| | | | | 2 | | | 1 | 8 | 280 | 110 | 4.4 | 715 | 0.393 | |
| | | | | 3 | | | 2 | 6 | 280 | 140 | 4.8 | 1040 | 0.571 | |
| 13 | (4-12) | 12Vc12 | PL<4,9% | 1 | 1 | | | 5 | 300 | 110 | 4.4 | 715 | 0.367 | Pt1=4,3,5,6,7,8,12<br>Pa3=4,9,14,13,16,17,12 |
| | | | | 2 | | | 1 | 6 | 300 | 140 | 4.8 | 1040 | 0.533 | |
| | | | | 3 | | | 2 | 7 | 300 | 110 | 4.4 | 715 | 0.367 | |
| | | | | 4 | | | 3 | 6 | 300 | 110 | 4.4 | 715 | 0.367 | |
| 14 | (12-9) | 6Vc12 | De<600µs | 1 | 1 | | | 3 | 684 | 90 | 3.6 | 585 | 0.132 | No disjoint paths available |
| | | | | 2 | | 1 | | 3 | 684 | 90 | 3.6 | 585 | 0.132 | |
| | | | | 3 | | 2 | | 2 | 620 | 60 | 2.4 | 390 | 0.097 | |
| | | | | 4 | | | 1 | 2 | 620 | 60 | 2.4 | 390 | 0.097 | |
| | | | | 5 | | | 2 | 3 | 684 | 90 | 3.6 | 585 | 0.132 | |
| | | | | 6 | | | 3 | 6 | 500 | 160 | 6.4 | 1040 | 0.320 | |
| | | | | 7 | | | 4 | 4 | 300 | 120 | 4.8 | 780 | 0.400 | |
| 15 | (7-16) | 50Vc12 | De<800µs | 1 | | 1 | | 4 | 720 | 90 | 3.6 | 585 | 0.125 | Po1=7,8,12,13,16<br>Po2=7,9,14,13,16 |
| | | | | 2 | | 2 | | 4 | 684 | 110 | 4.4 | 715 | 0.161 | |
| | | | | 3 | | 3 | | 5 | 500 | 130 | 5.2 | 845 | 0.260 | |
| | | | | 4 | | 4 | | 5 | 500 | 100 | 4 | 650 | 0.200 | |
| | | | | 5 | | | 1 | 4 | 720 | 90 | 3.6 | 585 | 0.125 | |
| | | | | 6 | | | 2 | 4 | 684 | 110 | 4.4 | 715 | 0.161 | |
| | | | | 7 | | | 3 | 5 | 500 | 130 | 5.2 | 845 | 0.260 | |
| | | | | 8 | | | 4 | 5 | 500 | 100 | 4 | 650 | 0.200 | |
| 16 | (7-16) | 15Vc12 | PL<5% | 1 | | 1 | | 4 | 720 | 100 | 4 | 650 | 0.139 | Pt1=7,8,12,13,16<br>Po3=7,9,14,13,16 |
| | | | | 2 | | 2 | | 5 | 500 | 110 | 4.4 | 715 | 0.220 | |
| | | | | 3 | | | 1 | 4 | 720 | 100 | 4 | 650 | 0.139 | |
| | | | | 4 | | | 2 | 5 | 500 | 110 | 4.4 | 715 | 0.220 | |
| | | | | 5 | | | 3 | 4 | 684 | 110 | 4.4 | 715 | 0.161 | |
| | | | | 6 | | | 4 | 5 | 300 | 130 | 5.2 | 845 | 0.433 | |

Table 3.4 Characteristics of the paths found in the German network sub-topologies

| Search number | S, D Nodes | Searched capacity | User Preferred | Path No | Tst | OACT | ACT | No-Hops | P-Max. Capacity (VC12) | Paths Length (Km) | Paths Loses (%) | Paths Delay (µs) | L/b | Disjoint Paths selected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 17 | (4-7) | 6Vc12 | De<500µs | 1 | 1 | | | 4 | 300 | 60 | 2.4 | 390 | 0.200 | Pt1=4,3,5,6,7 Pa4=4,9,14,13,7 |
| | | | | 2 | | 1 | | 4 | 300 | 60 | 2.4 | 390 | 0.200 | |
| | | | | 3 | | 2 | | 6 | 280 | 90 | 3.6 | 585 | 0.321 | |
| | | | | 4 | | | 1 | 4 | 300 | 60 | 2.4 | 390 | 0.200 | |
| | | | | 5 | | | 2 | 6 | 280 | 90 | 3.6 | 585 | 0.321 | |
| 18 | (14-12) | 10Vc12 | PL<3% | 1 | | 1 | | 4 | 700 | 100 | 4 | 650 | 0.143 | No path available |
| | | | | 2 | | 2 | | 3 | 500 | 80 | 3.2 | 520 | 0.160 | |
| | | | | 3 | | | 1 | 3 | 500 | 80 | 3.2 | 520 | 0.160 | |
| | | | | 4 | | | 2 | 4 | 700 | 100 | 4 | 650 | 0.143 | |
| | | | | 5 | | | 3 | 4 | 280 | 100 | 4 | 650 | 0.357 | |
| | | | | 6 | | | 4 | 5 | 280 | 110 | 4.4 | 715 | 0.393 | |
| 19 | (2-7) | 13Vc12 | PL <5% | 1 | 1 | | | 3 | 300 | 60 | 2.4 | 390 | 0.200 | No path available |
| | | | | 2 | | | 1 | 3 | 300 | 60 | 2.4 | 390 | 0.200 | |
| 20 | (8-14) | 8Vc12 | De<500µs | 1 | 1 | | | 5 | 684 | 120 | 4.8 | 780 | 0.175 | No path available |
| | | | | 2 | 2 | | | 6 | 320 | 160 | 6.4 | 1040 | 0.500 | |
| | | | | 3 | | 1 | | 4 | 500 | 80 | 3.2 | 520 | 0.160 | |
| | | | | 4 | | 2 | | 5 | 684 | 120 | 4.8 | 780 | 0.175 | |
| | | | | 5 | | 3 | | 6 | 320 | 160 | 6.4 | 1040 | 0.500 | |
| | | | | 6 | | | 1 | 4 | 500 | 80 | 3.2 | 520 | 0.160 | |
| | | | | 7 | | | 2 | 5 | 684 | 120 | 4.8 | 780 | 0.175 | |
| | | | | 8 | | | 3 | 6 | 684 | 130 | 5.2 | 845 | 0.190 | |
| | | | | 9 | | | 4 | 6 | 320 | 160 | 6.4 | 1040 | 0.500 | |

Table 3.5 Number of paths found in the German network sub-topologies

| Search number | Number of paths found in the TT | Number of paths found in the OACT | Number of paths found in the ACT | Disjoint pairs |
|---|---|---|---|---|
| **1** | 1 | 3 | 3 | 1 |
| **2** | 3 | 3 | 3 | 1 |
| **3** | 1 | 3 | 3 | 1 |
| **4** | 0 | 1 | 4 | 1 |
| **5** | 1 | 2 | 3 | 0 |
| **6** | 0 | 0 | 3 | 1 |
| **7** | 1 | 3 | 4 | 1 |
| **8** | 1 | 3 | 3 | 1 |
| **9** | 0 | 1 | 3 | 1 |
| **10** | 0 | 1 | 2 | 0 |
| **11** | 0 | 0 | 2 | 1 |
| **12** | 1 | 0 | 2 | 1 |
| **13** | 1 | 0 | 3 | 1 |
| **14** | 1 | 2 | 4 | 0 |
| **15** | 0 | 4 | 4 | 1 |
| **16** | 0 | 2 | 4 | 1 |
| **17** | 1 | 2 | 2 | 1 |
| **18** | 0 | 2 | 4 | 0 |
| **19** | 1 | 0 | 1 | 0 |
| **20** | 2 | 3 | 4 | 0 |
| **Total** | 15 | 35 | 60 | 13 |

# Abstract in Korean

향후 10년 간 지능적이고 유연한 구조의 인터넷이 필요한 광대역폭의 어플리케이션이 등장할 것에 대해 통신망 사업자와 통신장비 사업자 사이에 공감대가 형성되어 있다. 인터넷 프로토콜 (IP)을 광통시망에 적용하는 것은 통신망 전체의 성능을 향상할 뿐만 아니라 자본지출 및 운영지출을 감소시킬 것으로 기대된다. 자동화된 통신망 관리 시스템은 차세대 어플리케이션의 수요를 수용할 것이고 통신망 상에서 새로운 서비스가 작동하는 것을 허용할 것이다.

그러나 아쉽게도 이러한 전망은 실무선에서 현실화되지 못하고 있다. IP 사업부와 전송 사업부가 분리된 현재의 이동통신 사업자의 기업구조 하에서 두 부문의 통신망 관리 체계도 서로 이반되어 있다. 그리하여 기본적인 서비스를 제공하는 데 필요한 운영 조차도 자동화하기가 힘들고, 여러 부서의 인력이 함께 관여해야 시행되는 실정이다. 이러한 이유로, 이동통신 사업자는 현재의 수동 체계에서 벗어나는 방법을 모색 중이다.

현재의 분리된 IP 네트워크와 전송 네트워크가 직면한 이 문제를 해결하기 위하여, IETF와 ITU는 각각 표준화된 제어단계를 제시하였다. 이론상으로는, ITU-T와 IETF가 표준화한 ASON/GMPLS 제어단계 체계는 통신망 제어 및 관리와 관련된 문제를 해결하는 것으로 보이지만, 실제로 IP 계층과 전송 계층의 통합된 관리와 관련된 문제가 해결된 것은 아니다. 나아가서, 앞의 두 표준화 기구가 제안한 방식은 실무선에 있는 통신망 관리자에게 적합하지 않다.

이 졸업논문에서, 저자는 새로운 기술을 이식하는 데 드는 비용과 그 기술의 효율성을 추정하는 비용 모형을 소개하고, 다입력 다출력 중계자 모형을 제안한다. 나아가서, 저자는 관리 업무의 통합과 자동화를 진흥하기 위한 IP/MPLS 계층과 전송 계층 사이의 중계자 모형 구조를 제안하고, 인터넷 생태계 내에서의 가치 사슬에 대한 중계자 모형의 영향을 평가하며, 중계자 모형을 통해 SDH/SONET 통신망에서 다층 경로를 계산할 수 있음을 시연하는 알고리즘을제안한다.

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