Traffic Engineering in IP over Optical Transport Networks for Metropolitan and Wide Area Environments

SALVATORE SPADARO

ADVISOR: DR. JOSEP SOLÉ PARETA

COMPUTER ARCHITECTURE DEPARTMENT
UNIVERSITAT POLITÈCINICA DE CATALUNYA

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Resumen

La arquitectura de las redes de transporte actuales está basada en la tecnología de transporte SDH (*Synchronous Digital Hierarchy*). Las redes SDH se han diseñado y están optimizadas básicamente para el transporte del tráfico de voz. Actualmente, se está experimentando un crecimiento exponencial del volumen de tráfico de datos. Este crecimiento se debe a que el protocolo IP se está consolidando como capa de integración para servicios múltiples, algunos de ellos con requerimientos de Calidad de Servicio (*QoS*) y también a la introducción de tecnología de acceso de alta velocidad. Las características estadísticas del tráfico de datos son diferentes respecto a las del tráfico telefónico. De hecho, el tráfico IP se caracteriza no solo por su asimetría sino por su naturaleza dinámica, ya que presenta fluctuaciones o picos difíciles de predecir a priori.

Como consecuencia, ha surgido la necesidad de emigrar desde las actuales redes hacia una estructura más flexible y dinámica, optimizada para el transporte de tráfico de datos.

La evolución de las actuales redes de transporte incluye trasladar todas las funcionalidades de SDH (conmutación, monitorización de la calidad de la señal, protección frente a fallos) a nivel óptico. El resultado consistirá en una red de transporte óptica (*Optical Transport Network*, OTN) basada en tecnología DWDM, con *Optical Cross Connects* (OXC) para encaminar canales ópticos de forma permanente o conmutada (*Automatic Switched Optical Network*, ASON).

Uno de los principales problemas a solucionar por las operadoras de red es la eficiente gestión de la capacidad disponible, y así evitar por un lado la necesidad de sobredimensionar la red de transporte y por el otro optimizar la utilización de los recursos mediante la definición de estrategias de ingeniería de tráfico.

La introducción de las redes de transporte a conmutación automática (ASON), capaces de proporcionar conexiones ópticas bajo demanda, es considerada como la solución de red que puede proporcionar el rápido y flexible aprovisionamiento de ancho de banda. Tal funcionalidad, posible gracias a la definición de un plano de control basado en el paradigma GMPLS, puede ser usada para gestionar de manera dinámica los recursos disponibles, tanto a nivel SDH como a nivel óptico, respondiendo de forma eficiente a las fluctuaciones del tráfico generado por la red cliente.

Sin embargo, el problema que surge es el diseño de un mecanismo para disparar automáticamente las peticiones de establecimiento de circuitos SDH/canales ópticos conmutados.

En este sentido, la primera contribución de esta Tesis es el diseño de un mecanismo de disparo de peticiones de circuitos SDH/canales ópticos basado en la monitorización y predicción del tráfico de la red cliente (IP). Además, el mecanismo diseñado incluye la definición de políticas de

ingeniería de tráfico para la optimización de la utilización del elevado ancho de banda proporcionado por las conexiones ópticas. Concretamente, el mecanismo diseñado se caracteriza por la interoperabilidad entre la capa cliente y la capa de transporte.

La Tesis incluye también una contribución sobre el diseño de una metodología para el dimensionado de la redes ASON, basada en la caracterización del tráfico de llegadas de peticiones de establecimiento de conexiones, mediante su valor medio y el factor de *peakedness*.

Por otro lado, la optimización de los recursos disponibles es muy crítica cuando se produce un fallo en la infraestructura de red debido a la necesidad de encontrar rutas alternativas para el tráfico afectado. Debido al gran volumen de tráfico a transportar, un fallo en la infraestructura de red puede tener graves consecuencias económicas. Por ejemplo, un corte de una única fibra óptica produce el fallo de todas las longitudes de onda que transporta; de esta manera la pérdida de cada longitud de onda operante a 2.5 Gbps o 10 Gbps puede resultar en el corte de un enorme número de conexiones en curso. Por lo tanto, a mayor capacidad, mayor es la importancia de la rapidez y rendimiento de los mecanismos de protección y recuperación.

Las estrategias de protección frente a fallos deben ser simples, minimizar las pérdidas de tráfico y deben utilizar eficientemente los recursos disponibles.

La recién estandardizada tecnología para redes de entornos metropolitanos, *Resilient Packet Ring* (RPR) se caracteriza por mecanismos de protección optimizados para minimizar el tiempo de recuperación en caso de fallos. Además, tales mecanismos no requieren la asignación a priori de recursos de red a utilizar solamente en caso de fallos.

Por lo que respecta a los mecanismos de recuperación, se puede optar por una estrategia de recuperación en una sola capa (*single layer recovery*) o alternativamente por una estrategia de recuperación en múltiples capas (*multi-layer recovery*), donde en la recuperación intervienen diferentes capas de la estructura de red. El esquema de recuperación multi-capas más fácil de implementar es el consistente en ejecutar los mecanismos de protección/recuperación de los distintos niveles de manera paralela e independiente. Esta estrategia no es, sin embargo, la más eficiente. La interoperabilidad entre los mecanismos de protección de las diferentes capas permite reaccionar más rápidamente a los fallos que se pueden producir.

La segunda contribución de esta Tesis es el diseño de una política de coordinación entre los mecanismos de protección proporcionados por RPR y los mecanismos de protección definidos por la capa óptica. Concretamente, la estrategia diseñada se basa en la interoperabilidad entre la capa

RPR y la capa de transporte (OTN) para redes de entornos metropolitanos. La estrategia diseñada permite, además, la optimización de los recursos de red.

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Acronyms

APS	Automatic Protection Switching
ASON	Automatically Switched Optical Network
ASTN	Automatically Switched Transport Network
ATM	Asynchronous Transfer Mode
BoD	Bandwidth on Demand
CAPEX	Capital Expenditure
CC	Connection Controller
DCN	Data Communication Network
DPT	Dynamic Packet Transport
EGP	Exterior Gateway Protocol
ESCON	Enterprise Stems Connection
FDDI	Fibre Distribution Data Interconnection
FICON	Fibre Connection
FSC	Fibre Switch Capable
GFP	Generic Framing Procedure
GMPLS	Generalized Multi-Protocol Label Switching
GoS	Grade of Service
HDLC	High Level Data Link Control
HOVC	High Order Virtual Container
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IP	Internet Protocol
ISDN	Integrated Services Digital Network
IS-IS	Intermediate System – Intermediate System
ITU-T	International Telecommunications Union – Telecommunications Sector
LCAS	Link Capacity Adjustment Scheme
LDP	Label Distribution Protocol
LMP	Link Management Protocol
LoL	Loss of Light
LoS	Loss of Signal
LOVC	Low Order Virtual Container
LRM	Link Resource Manager
LSP	Label Switched Path
MAC	Medium Access Control
MEMS	Micro Electro Mechanical Systems
MIB	Management Information Base
MPLS	Multi-Protocol Label Switching
NNI	Network Network Interface
OADM	Optical Add and Drop Multiplexer
OIF	Optical Internetworking Forum
OPEX	Operational Expenditure
OSPF	Open Shortest Path First

OSS	Operational Support System
OTN	Optical Transport Network
OXC	Optical Cross-Connect
PC	Permanent Connection
PDH	Plesiochronous Digital Hierarchy
PoS	Packet over SONET/SDH
POTS	Plain Old Telephone Service
QoS	Quality of Service
RC	Routing Controller
RPR	Resilient Packet Ring
RSVP	Reservation Resource Protocol
RWA	Routinf and Wavelenght Assignment
SC	Switched Connection
SDH	Synchronous Digital Hierarchy
SNMP	Simple Network Management Protocol
SONET	Synchronous Optical Network
SPC	Soft Permanent Connection
SRP	Spatial Reuse Protocol
SRP-fa	Spatial Reuse Protocol-fairness algorithm
TC	Traffic Controller
TDM	Time Division Multiplexing
TE	Traffic Engineering
UNI	User Network Interface
VC	Virtual Container
VCAT	Virtual Concatenation
VCG	Virtual Containers Group
VPN	Virtual Private Network
WDM	Wavelength Division Multiplexing

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Abstract

The main objective of the traffic engineering (TE) strategies is the efficient mapping of the actual traffic onto the available network resources.

Legacy Time Division Multiplexing-based networking architecture was basically designed to transport symmetric voice traffic. However, the volume of data traffic is increasing at explosive rate and already dominates the voice traffic. This is due to a progressive migration of many applications and services over the Internet Protocol (IP) and also to a deeper and deeper introduction of high-speed access technologies. Also there is the convergence towards the IP of real-time applications (i.e. multimedia applications) which have very strict QoS requirements.

The statistical characteristics of the data traffic are rather different from those of telephone traffic. Specifically, IP traffic is highly dynamic showing predictable and unpredictable traffic surges/peaks. Such surges are caused by unexpected events such as user' behaviours, weather conditions, accidents, fault, etc. This can cause significant fluctuations of the aggregated data traffic to be carried by the transport networks.

The current SONET/SDH transport networks (but also the incoming Optical Transport Networks) tend to be static, which means that connections (SONET/SDH circuits and light paths) are provided manually through the Network Management System. The manual configuration is time consuming, which means that weeks or even months are needed to provide high bandwidth connections.

The highly dynamic IP traffic pattern does not match with the static provisioning of capacity of the optical transport networks, leading to non-optimal utilization of the resources (i.e. network congestion or under-utilization of resources).

Thus, the problem that arises for Network Operators is how to efficiently manage the network resources in the transport network to efficiently respond to the changes in the traffic demands reaching, in such a way, traffic engineering objectives.

The introduction of the Automatic Switched Optical Networks (ASON), which is able to provide dynamically switched connections on demand, is recognized as the enabling solution to meet the requirement of fast and flexible end-to-end bandwidth provisioning. The automatic set up and tear down of optical connections can be used for the dynamic management of the transport network resources to track significant variations in the volume of the network client traffic. In such a context, a mechanism that triggers demands to set up/tear down light paths as a function of the variation of the client traffic to be transported is required.

The design of a multi-layer traffic engineering (MTE) strategy for IP/MPLS over ASON/GMPLS networks to face with the dynamic traffic demands is the first contribution of this Ph.D. Thesis. It has to be underlined that the policies for the set up of the light paths are out of the scope of this work. In fact, it is assumed that the set up/tear down of the switched connections is in charge of the ASON control plane, namely the GMPLS-based routing and signalling protocols.

As a second contribution, it is presented a practical approach for ASON networks dimensioning purposes based on the approximate characterization of the traffic arrival process, through its mean and the peakedness factor.

On the other hand, the optimization of the utilization of network resources is very critical when failures occur in the network as a consequence of the need of rerouting the affected traffic. The increase of the capacity and number of wavelengths that can be multiplexed onto the same fibre, each one carrying 2.5 or 10 Gbps client signals, implies that outages of the network infrastructure can have serious economical and social consequences.

Network recovery/resilience, i.e., the capability of the networks to efficiently recover from failures, has become of vital importance. Thus, optical transport networks need to be very robust to face failures. The protection mechanisms should be designed basically with the aim to be simple, to minimize the traffic losses and to optimize the utilization of the network resources.

Survivability strategies in current transport networks are based on the pre-allocation of network resources to be used only to switch (route) the affected traffic in case of failures.

In legacy multi-layer networks, each layer (e.g. IP, SDH) has its own protection mechanism built in, independent from the other layers. Network recovery basically relies on the SONET/SDH network layer. Indeed, different mechanisms, based on the protection approach, have been proposed that allow fast recovery within the target of 50 ms. Nevertheless, SONET/SDH protection is mainly limited to ring topologies and it is not able to distinguish between different priorities of traffic and it has not vision of higher layer failures.

The emerging packet-based Resilient Packet Ring (RPR) technology for metropolitan networks provides powerful protection mechanisms that minimize the time needed to restore the traffic without the pre-allocation of resources.

To face to failures, the resilience single-layer strategy (a single layer has the responsibility for the recovery) is very simple from the implementation point of view. However it may not be able to efficiently recover the network from all kind of failures that can occur. Therefore, multi-layer resilience (various network layers can participate to the recovery actions) provides better performance not only in terms of protection but also in terms of resources optimization.

Multi-layer resilience strategies require coordinating the recovery mechanisms provided by each layer. In such a context, another contribution of this Ph.D. Thesis is the design and evaluation of a multi-layer resilience mechanism to be used in the IP over RPR over intelligent optical transport network for metropolitan environment to efficiently face with a wide range of network outages, while optimizing the utilization of the network resources. Its novelty relies on the interworking required between the RPR and the optical transport layer.

Finally, the fourth contribution of the Thesis deals with the optimization of the bandwidth utlization of the RPR rings taking benefits from the automatic switching of optical connections capabilities of the underlying ASON/GMPLS networks.

1 Introduction

Legacy networking architecture is based on a client layer (Layer 3) on top of the transport network. The classic telecom mapping was based on a multi-layer architecture composed by the Internet Protocol (IP), which is actually the clear dominator among layer 3 protocols, while the transport network was composed by Asynchronous Transfer Mode (ATM) layer over Synchronous Optical Networks/Synchronous Digital Hierarchy (SONET/SDH) layer over Wavelength Division Multiplexing (WDM) technology [1]. This networking architecture (Figure 1) is an effective solution in a voice-centric scenario where IP is just one of the clients of the transport network. In such a network context, IP packets, whose length is variable (from 40 bytes to 1500 bytes) are segmented into ATM cells of fixed length [1]. Then, the ATM cells are assigned to different Virtual Connections (switched through ATM core switches), packed into SONET/SDH frames according to the SONET/SDH multiplexing hierarchy, and transported through the SONET/SDH transport network (onto bi-directional circuits). The transport capacity of the fibres interconnecting the SDH Digital Cross Connects (DXCs)/Add Drop Multiplexers (ADMs) is highly increased through the utilization of the WDM technology that allows different wavelengths to be multiplexed on a single fibre [2], [3]. The resulting network is thus a multi-layer architecture requiring different equipments for each layer and where each layer has to be maintained and managed independently from the others. Moreover, it presents many drawbacks such as heavy overall overhead, partial overlapping of functions (e.g., protection, management functions) and very high costs for Network Operators.

1.1 Transport Network evolution path

The first step in the networking architecture evolution has been the elimination of the ATM layer. The fact that the SONET/SDH network was kept at layer 1 still ensured all the advantages of

SONET/SDH transport networks, among which protection, digital performance monitoring, and complete network management capabilities.

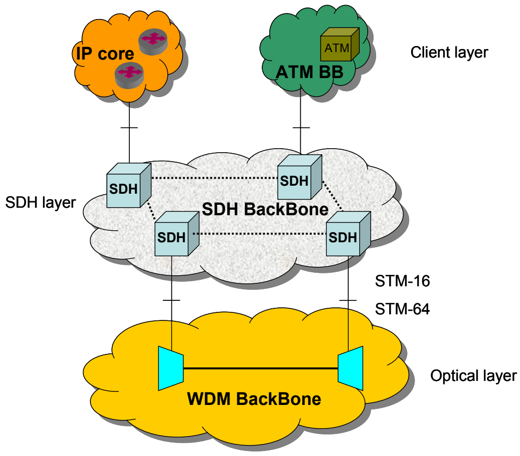


Figure 1: Legacy networking architecture

Time Division Multiplexing (TDM) legacy transport networks (e.g., SONET/SDH) have been basically designed for voice and leased line services (SONET/SDH technology was initially designed to optimize transport of 64 kb/s-based TDM services). In the past ten years many network operators have largely deployed SONET/SDH transport infrastructures in both long haul and metropolitan/regional networks.

However, today it is widely recognized that the traffic expected to be carried by the public transport networks will be progressively dominated by data, which is growing at explosive rate. This is due to the migration of many applications and services over IP and also to a progressive introduction of high-speed access technologies [4]. Indeed, emerging applications are fuelling the growing of data-traffic. Some examples of such emerging applications are: high-bandwidth multi-media applications (real-time and no-real-time), shared access to remote resources, network-wide computation and data services (grid-computing, data-grid), storage networking, disaster recovery, etc. In this context, another important point of attention is that the convergence towards the IP of real-time applications (i.e. multimedia applications) imposes very strict QoS requirements such as latency, jitter, packet loss, etc.

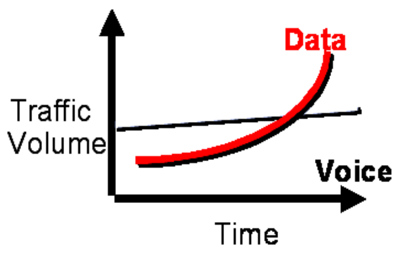
On the other hand, traditional IP routing algorithms (i.e. Open Shortest Path First (OSPF), Interior Gateway Protocol (IGP) and Intermediate System-Intermediate System (IS-IS)) do not provide an efficient distribution of traffic load onto available network resources [5]. Indeed, when IP traffic is carried by bi-directional SONET/SDH circuits, large portions of the network bandwidth may remain under-utilized, while the bandwidth at the opposite direction can be congested [6]. IP traffic is characterized by its typical asynchronous, burst and asymmetric nature in contrast to the traditional symmetric telephone traffic [7] and [8].

With the rapid growth and dynamicity in demand for network resources, both fast bandwidth provisioning and Traffic Engineering (TE) are key requirements for the next generation transport networks. Some of the TE objectives are efficiently mapping the actual traffic to available network resources and manage traffic as well as network capacity rapidly and effectively in response to changes in the traffic pattern. Specifically, according to [9] it is the process to control traffic flows in a network in order to optimize resources utilization and network performance. Practically, this means choosing routes taking into account traffic load, network state and user requirements such as QoS or bandwidth, and moving traffic from more congested paths to less congested ones.

The dynamic changes in the client traffic pattern are the consequence, for example, of sudden fluctuations of the traffic due to unexpected events (e.g. disasters) or equipments failures.

In legacy networks, TE issues relied on the ATM technology, basically thanks to its connection-oriented nature and due to the decoupling of routing (control plane) and forwarding (data plane) functionalities [1]. Nevertheless, the IP over ATM mapping increases the network complexity since IP is ATM unaware and hence two separate control planes were needed. Thus, Internet Engineering Task Force (IETF) developed the Multi-Protocol Label Switching (MPLS) technology as a tool to provide TE features to the IP networks [10]. Nevertheless, it is recognised that TE in the IP-MPLS layer may not be sufficient in backbone networks [4].

The evolution path of current transport networks is characterized by a data-centric networking scenario (Figure 2). Such evolution will encompass different steps depending on the time scale it is considered for such evolution [11], [12] and [13].



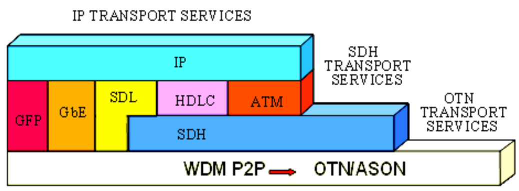


Figure 2: Evolution path towards data-optimized networks

The short-term step in the network evolution is based on the addition of new network functionalities (i.e. dynamic bandwidth allocation) to legacy SONET/SDH networks through the implementation of the Virtual Concatenation (VCAT) and Link Adjustment Capacity Scheme (LCAS) paradigms [14], [15]. The SONET/SDH payload bit rates are rigid since they were originally designed for traditionally voice networks. VCAT tries to relax this characteristic. It consists basically on breaking the payload into individual channels (called members of the Virtual Concatenation Group, VCG), transporting each channel separately, and then recombining them into a contiguous bandwidth at the endpoint of the transmission. This functionality is needed only at the path termination equipments.

With the LCAS definition, the number of concatenated payloads (members) may be increased or decreased at any time without affecting traffic currently being sent. Moreover, LCAS will automatically decrease the capacity if a member of VCG experiences a failure in the network. Specifically, when one of the constituent channels experiences a failure, it will be automatically removed while the remaining channels are still working. Thus, the available bandwidth will be lowered but the connection will be maintained.

The second step in the network evolution path encompasses, in a middle-term scenario, for both metropolitan and wide area environments, the elimination of SONET/SDH network layer.

Indeed, the transport capabilities of SONET/SDH (e.g. protection and accommodation of various bit rates through tributaries) are being absorbed by the optical layer thanks to the advances of optical technology [16], and the standardization of the Optical Transport Network (OTN) [17]. An OTN is composed by a set of optical network elements (Optical Cross-Connects (OXC) and Optical Add Drop Multiplexer (OADM)) connected by optical fibre links. OTNs are able to provide the network functionality of transporting, multiplexing, routing, management, supervision and survivability of optical channels carrying client signals, avoiding the electronic process of the data at intermediate nodes. A distinguishing characteristic of the OTN is its provision of transport for any digital signal independently of client-specific aspects, i.e., it provides client layer independence.

The transport networks (both legacy SONET/SDH and incoming OTN) tend to be static, which means that connections (both SONET/SDH circuits and light paths in OTNs) are provided “manually” through the NMS (i.e., permanent connections). This way of provisioning is rather time consuming, which means that weeks or even months are needed to provide high bandwidth connections.

The further step of the network evolution path, in a long-term scenario, comprises the introduction of the Automatically Switched Optical Networks (ASON) [18]. While current optical networks only provide transport capacity, the main feature of an ASON is the ability to automatically increase/decrease the transmission capacity on demand (client request), i.e., setting up/tearing down optical channels automatically and automatic neighbouring discovery as well. To provide such network functionalities, a Control Plane (CP) has to be defined. The GMPLS (Generalized Multi-Protocol Label Switching) paradigm is proposed to be the control plane for the ASON networks. It is an extension of the set of protocols designed for the MPLS technology and it encompasses time-division (e.g. SONET/SDH, Plesiochronous Digital Hierarchy (PDH), G.709 [111]), wavelength, and spatial switching (e.g. incoming port or fibre to outgoing port or fibre) [19]. The implementation of a GMPLS-based control plane allows an integrated vision of the network, namely the integration between the client layer and the optical transport layer. It is recognized that such integration leads to lower networks cost and complexity [20], [21].

The introduction of intelligence by means the CP is recognized as the enabling solution to meet the requirements, among others, of fast and flexible end-to-end bandwidth provisioning, automatic topology discovery and fast restoration.

In this context, one of the main topics to be solved is how to dynamically manage the capacity available at optical level, in order to transport the client traffic in a cost-effective way, while optimizing the utilization of the network resources, reducing the network complexity and inefficiency of legacy transport networks.

Focusing particularly in the metropolitan network context, many networks use a physical ring structure. This is a natural environment for the SONET/SDH networks that constitute the bulk of current metropolitan network infrastructure. As mentioned above, SONET/SDH, however, was designed for point-to-point circuit-switched services. Alternatively, Ethernet technology offers a simpler and inexpensive solution for data traffic. However, because Ethernet is optimized for point-to-point or meshed topologies, its use of the available bandwidth is inefficient and it does not take advantage of the ring topology in order to implement a fast protection mechanism [22].

The emerging Resilient Packet Ring (RPR) Layer 2 technology, recently standardized by the Institute of Electrical and Electronics Engineering (IEEE) as IEEE 802.17 RPR, fills this gap by being a multi-service transport protocol based on packets rather than circuits [23]. RPR systems are seen by many carriers as the inevitable successors to SONET/SDH ADM-based rings in metropolitan networks, allowing moreover higher revenues expectations [24]. This is due to the fact that RPR networks may provide performance-monitoring features similar to those of SONET/SDH and, at the same time, maintain Ethernet's advantages, i.e., low equipment cost, high bandwidth granularity and statistical multiplexing capability. Furthermore, the RPR may run over the fibre (dark fibre or WDM).

For carriers, RPR promises the delivering of all the necessary end-user services, such as TDM voice, Virtual Private Networks (VPN) data and Internet access, at dramatically lower equipment, facility and operating costs.

The optimization of the utilization of network resources is very critical when failures occur in the network (as a consequence of the need of rerouting the affected traffic). Indeed, network survivability/resilience/recovery, namely the capability of the network to recover traffic affected by failures, has become of vital importance in current networks and next generation networks will need to be very robust to face failures [25], [26]. Network Operators, therefore, have to take special precautions in order to prevent this, which means doing their networks survivable. As it is difficult to prevent failures in the network infrastructure (equipment failures, cable breaks, etc.) the objective is to maintain service availability even under failure conditions. In order to make the networks more reliable the networks has to be reconfigurable. This reconfiguration has to be fast and optimizing the utilization of the network resources. Finally, it has not to increase too much the cost of the network.

The protection mechanisms implemented in RPR are fast. In fact, they aim to achieve recovery times of about 50 ms and to protect against any single failure in the ring. No bandwidth is dedicated for recovery purposes and, therefore, in a failureless state the resource utilization is very high.

On the other side, the achievements in the optical layer thanks to the standardization of the OTN and the ASON/GMPLS paradigm allow recovery capabilities directly in the optical layer.

To face to failures, the resilience single-layer strategy (a single layer has the responsibility for the recovery) is very simple from the implementation point of view. However it may not be able to efficiently recover the network from all kind of failures that can occur. Therefore, multi-layer resilience (various network layers can participate to the recovery actions) provides better performance not only in terms of protection but also in terms of resources optimization. However, it requires coordinating the recovery mechanisms provided by each layer.

In metropolitan IP over RPR over intelligent optical layer, to improve the overall network resources utilization in case of failures, efficient strategies to coordinate the recovery mechanism implemented at RPR layer and at the OTN layer have to be defined. The aim is to provide not only survivability but also overall network resources optimisation, which means meeting TE objectives.

1.2 Problems addressed in this Ph.D. Thesis

This Ph.D. Thesis deals with the design of multi-layer traffic engineering (MTE) strategies both for metro and wide area networks. Specifically, two MTE procedures have been designed and evaluated, namely one for IP/MPLS over ASON/GMPLS network scenario to face with the dynamic traffic fluctuations at the client network, and another for metropolitan IP over RPR over intelligent optical transport networks scenario to face with the efficient recovery from failures.

The optimization of network resources means the efficient transport of client network traffic on the optical transport network. The aim is to avoid network congestion due to the unexpected events, such as traffic variations or network failure, as well as optimizing the optical resources bandwidth utilization.

In the case of the Wide Area Networks environment, we concentrate on transporting IP/MPLS over intelligent optical transport networks. The automatic optical connections set up/tear down introduced by the definition of ASON/GMPLS paradigm allows the design of efficient MTE to cope with dynamic bandwidth demands.

Moreover, we designed a practical approach for ASON networks dimensioning purposes based on the approximate characterization of the traffic arrival process, through its mean and the peakedness factor.

In the case of the metropolitan networks, we concentrate on the design and evaluation of interworking mechanisms for a short-term network solution in the evolution path, which implies to suppress the SONET/SDH layer and considering the very promising solution represented by Resilient Packet Ring technology. Given the necessity to make the network reliable, a multi-layer resilience strategy in the IP over RPR over optical transport networks to recover efficiently from a vast range of possible networks outages is designed and evaluated. Its novelty relies on the interworking required between the RPR and the optical transport layer.

The optimization of the bandwidth utilization of the RPR rings taking benefits from the automatic switching of optical connections capabilities of the underlying ASON/GMPLS networks has also been addressed.

It has to be underlined that the work here presented has been part of the research activities performed by the Advanced Broadband Communication Centre (CCABA) of the Universitat

Politècnica de Catalunya. In particular, the work was carried out within the framework of the international research project IST-1999-11387 “Layers Interworking in Optical Networks (LION)” funded by the European Commission and within two national projects, namely “Evaluación de arquitecturas de conmutación de paquetes para redes ópticas (ECOPAQ)” funded by the Spanish Ministry of Education under contracts TIC99-0572-C02-02 and “Transporte de trafico IP sobre redes opticas: diseño y evaluación (TRIPODE)” funded by MCyT (Spanish Ministry of Science and Technology) under contracts FEDER-TIC2002-04344-C02-02.

This Ph.D. Thesis is organized in three parts. The first one is devoted to the capacity management problem in next generation networks. It includes the Chapters 2, 3 and 4. Specifically, Chapter 2 focuses on the multi-layer TE in IP/MPLS over ASON/GMPLS presenting the considered scenario and the related works. Chapter 3 describes the procedure suggested on this topic. Specifically, it presents the TRIDENT procedure highlighting its characteristics and merits. Chapter 4 deals with the traffic modelling for the dimensioning of the ASON networks. In particular, it presents the investigations about the suitability of classical teletraffic models for ASON dimensioning purposes.

The second part deals with the design of a multi-layer resilience strategy able not only to efficiently react to failures but also to optimise the network resources utilisation in case of failures. It includes Chapter 5 and Chapter 6. Specifically, Chapter 5 discusses the related work on the multi-layer recovery approach while Chapter 6 discusses on one hand the strengths and weakness of the RPR technology and on the other hand, it presents the MTE strategies designed to be used in IP over RPR over intelligent optical networks for metropolitan environments.

Chapter 7 draws some conclusions while Chapter 8 discusses some possible future works which arise from the contributions of this Thesis.

Finally, the Thesis includes a third part, including three Chapters. Chapter 9 presents in detail the TRIDENT procedure and Chapter 10 presents the experimental implementation of the TRIDENT procedure in a real environment, namely in the ASON-GMPLS testbed developed at the Telecom Italia Lab premises. In particular, the feasibility of the procedure is evaluated and some experimental results are depicted and discussed. Finally, Chapter 11 describes the generalization of the TRIDENT procedure to dynamic SDH-based networks, namely legacy SDH networks improved by the application of the VCAT and LCAS functionalities.

PART I: Multi-layer TE in ASON Transport Networks

This part of the Thesis deals with the capacity management issues in next generation transport networks. Firstly the problem is formulated, some related works are discussed and finally we present TRIDENT, a multi-layer traffic engineering procedure designed to efficiently track the fluctuations of the IP/MPLS traffic, while optimising the network resource available at the transport optical layer. Specifically, its characteristics and merits are discussed and evaluated by simulation.

This part is concluded by a practical contribution of this Thesis which deals with the suitability of classical teletraffic models for ASON dimensioning purposes.

2 Multi-layer Traffic Engineering in IP/MPLS over ASON/GMPLS networks

Next generation transport network infrastructures have to cope with the growing demand for bandwidth generated by the client layer as well as have to be multi-service, namely able to support several traffic classes with different requirements in terms of Quality of Service (QoS) [27].

It is widely recognized that the traffic in evolutionary transport networks will be progressively dominated by data. As a matter of fact, the statistical characteristics of data traffic are rather different from those of traditional voice traffic, for which legacy TDM-based transport networks have been designed and optimized.

In fact, firstly IP traffic is characterized by its asymmetry and secondly it is highly dynamic; it is not as easily predictable and stable as the voice traffic, and it shows predictable and unpredictable surges/peaks as well. Such surges are caused by unexpected events such as users' behaviour, weather conditions, accidents, faults, etc., which cause significant and unexpected fluctuations over time (e.g. on a daily basis) of the aggregated data traffic to be transported by the telecommunication networks.

With such data traffic nature, a very simple dimensioning approach relies on the bandwidth over-provisioning, namely over dimensioning the network resources in order to take into account the peaks of the traffic that has to be carried. Nevertheless, such approach does not represent a cost-effective solution since Network Operators may want to reduce both the infrastructure Capital Expenditure (CAPEX) and Operational Expenditure (OPEX).

Alternatively, the data traffic peaks/burst can be handled by the provisioning of bandwidth through the Network Management System (NMS), using a bandwidth scheduled approach [28]. In such a case, the bandwidth is allocated for example on the basis of the time of the day. The easiest way but, at the same time the most inefficient, to implement this approach is over dimension the entire network and modify the traffic policy done at the client router depending on the time. Another possibility to make the system more efficient, from a bandwidth point of view, is to trigger, as we point out in the next Section, User Network Interface (UNI) set up signalling from the client or server router depending on the time to allocate more bandwidth.

However, when IP traffic has to be carried, although the periodic nature of the traffic pattern (similar periodic pattern can be observed on network links during the same periods, See Figure 3 and Figure 4), the data traffic volume to be transported is not predictable since it is difficult to know how huge the surges are. As an example, if we compare the traffic monitored from the Catalan Research &Academic Network [29] for two different working weeks, the traffic volume is not easily predictable.

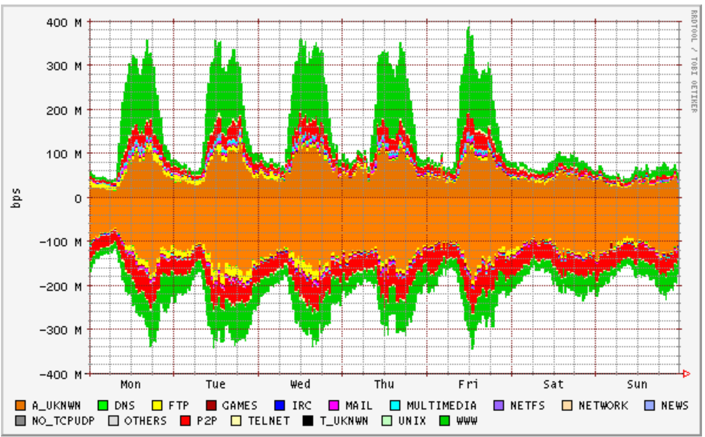


Figure 3: Weekly incoming/outgoing traffic from the Catalan R&A Network, November 2004, 8-15

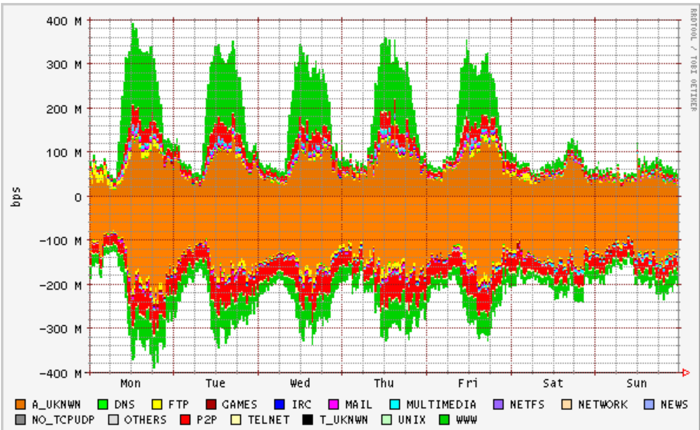


Figure 4: Weekly incoming/outgoing traffic from the Catalan R&A Network, October 2004, 25-31

Moreover, such approach requires detailed investigations about the behaviour of the different clients of the transport network.

As a consequence, the basic requirements for next-generation optical transport networks are the flexibility and the ability to dynamically react to traffic demand changes, allowing at the same time the optimization of the network resources [4], [30].

2.1 Capacity Management for network resources optimization

In order to provide TE capabilities in the Internet network context, the Internet Engineering Task Force (IETF) introduced MPLS technology [10], and the Constraint Based Routing (CBR) feature [31].

MPLS decouples routing and signalling (control plane) and forwarding (data plane). Such technology is based on the encapsulation of IP packets into labelled packets that are forwarded in a MPLS domain along virtual connections called Label Switched Paths (LSPs). MPLS-enabled routers are called label switched routers (LSRs). Each LSP can be set up at the ingress LSR by means of ordered control before packet forwarding.

Constraint-based routing means that when a route is calculated (for example for a MPLS LSP) not only network topology but also user's requirements have to be taken into account [27]. An LSP can be forced to follow a route that is calculated a priori thanks to the explicit routing function. Then, the network resources are reserved on the specific path by means of suitable signalling protocols (e.g. Resource Reservation Protocol [32] and Label Distribution Protocol [33]). Moreover, each LSP can be set up, torn down, rerouted if needed, and modified by means of the variation of some of its attributes. Furthermore, pre-emption mechanisms on LSPs can also be used in order to favour higher priority data flows at the expense of lower priority ones, while avoiding congestion in the network.

MPLS is IP aware and introduces a single IP control plane and thus the network scalability is easier with respect to the IP over ATM architecture. However, it is recognised that MPLS is not sufficient to provide efficient mechanisms for TE in the network backbone segments [4].

The efficient management and control of the growth of bandwidth demands from data traffic and the need of the Network Operators to reduce investments and operative costs (CAPEX and OPEX) represent two of the major drivers moving the evolution of current transport networks, both in the long-haul and metro segments [34], [35].

The introduction of intelligence in the transport networks (i.e. the ability to set up/tear down high bandwidth connections dynamically), is considered a promising solution to meet the above mentioned emerging requirements. This new functionality is obtained by the implementation of a distributed control plane (CP), which consists of a set of functionalities such as signalling and routing distributed throughout the network.

2.1.1 Automatically Switched Optical Network (ASON)

The standardization of the Automatically Switched Optical Network (ASON) [18], which is able to provide dynamically optical bandwidth (i.e. light paths) on the basis of the client layer requests, is recognized as the enabling solution to meet the requirement for fast and flexible end-to-end bandwidth provisioning. An ASON is an optical transport network supporting a Transport Plane, a Control Plane and a Management Plane (Figure 5). The Transport Plane provides bi-directional or unidirectional information flows transfer between users while the Management Plane is responsible for fault, performance, configuration, accounting, and security management functions both for the transport and control planes. ASON networks provide leased optical lines (Permanent Connections established through the NMS) and other two innovative transport services: Soft Permanent Connections (SPC) and Switched Optical Connections (SC).

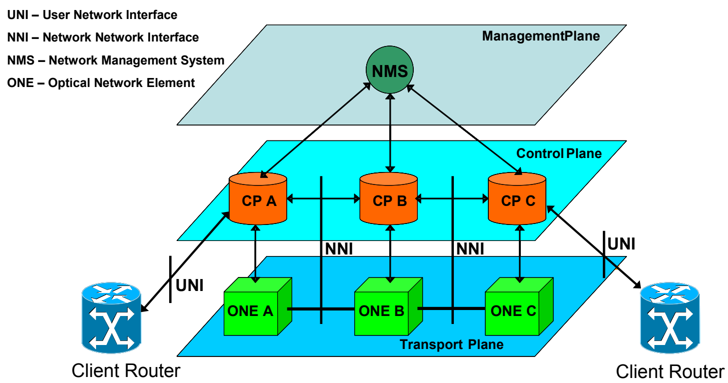


Figure 5: ASON Reference network model

The SPC (Figure 6 (a)) is requested by the management plane, which uses network generated signalling and routing protocols via the Network to Network Interface (NNI) to establish the connections, while the switched service (Figure 6 (b)) is requested directly by the customers via UNI signalling; then the connections are set-up using NNI signalling and routing protocols. A distributed GMPLS-based Control Plane (CP) has to be implemented to achieve the above automatic switching network features. Basically, the CP consists of the set of routing and signalling protocols needed to set up or release switched connections according to users' requests or restore connections in case of failures.

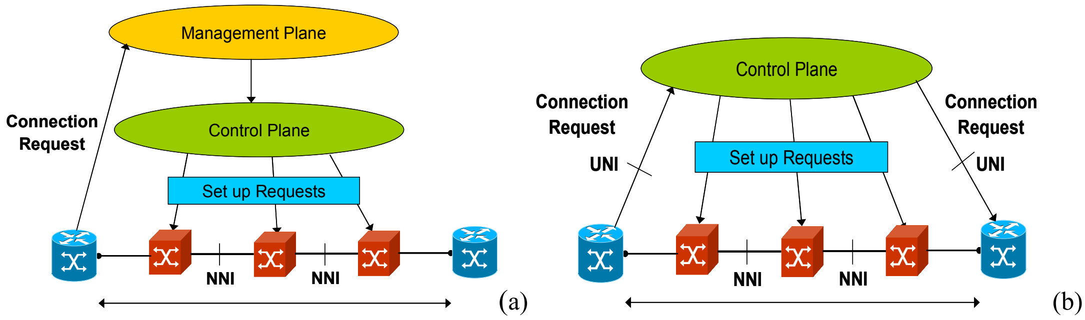


Figure 6: ASON transport services, (a) soft-permanent connection, (b) switched connection

Basically the Internet Engineering Task Force (IETF) [36] and Optical Internetworking Forum (OIF) [37] have been defining the generalization of MPLS control plane (Generalized MPLS) to control the optical components (OXCs and OADMs) and thus being viable the implementation of the CP functions for ASON networks.

Basically, the CP is in charge of: 1) Fast and efficient configuration of connections within the transport layer network to support both switched and soft permanent connections, 2) Reconfiguration or modification of connections that support calls that have previously been set up and 3) Performing restoration functions directly in the optical layer in case of failures.

The control plane defined for ASON consists of components with diverse functionalities. Interactions of these components and the information needed for a communication between components are done via interfaces (e.g., UNI and NNI). The main components of the ASON CP are (Figure 7) [18]:

- **Connection Controller (CC)**: it is the responsible for the coordination among all the control plane components for the purpose of the management and supervision of connection set ups, releases and the modification of connection parameters for already established connections.
- **Routing Controller (RC)**: it responds to requests from connection controllers for path information needed to set up connections and respond to requests for topology information for network management purposes.
- **Link Resource Manager (LRM):** it is responsible for the management of connections among ports, lambdas, of the transport plane elements. Moreover it provides information about the physical characteristics of the nodes to the CC.

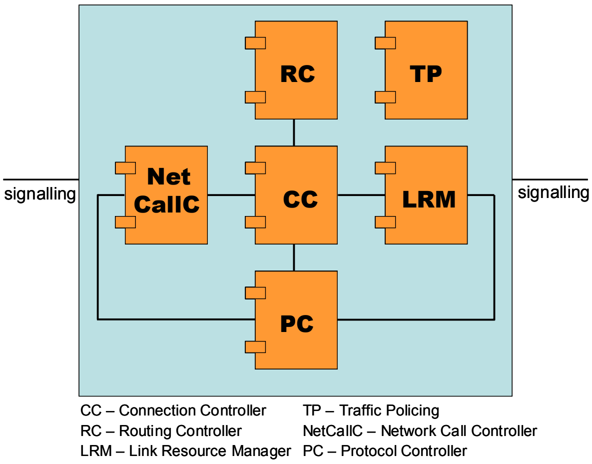


Figure 7: ASON Control Plane

For the communication among the control plane components of the network nodes a "signalling network" is required. Such signalling network is called Data Communication Network (DCN) and among its requirements, it is important to highlight the reliability and the transmission capacity. The former relies on the ability to recover from failures and the latter is essential to avoid high propagation delays with consequent high set up times. The set up time is strongly related for example to the recovery time in case of failures recovered at the optical layer (e.g. fast restoration).

The implementation of a control channel (i.e. unidirectional channel between two adjacent nodes of the signalling network) can be obtained as follows [38]:

- **Out-of-fibre/Out-of-band**: the DCN is implemented with an independent network such as Ethernet or IP networks
- **In-fibre/Out-of-Band**: the DCN is implemented by using one among the WDM channels, which is dedicated to the signalling.
- **In-Fibre/In-Band**: the signalling information is transmitted using for example the overhead of the SONET/SDH frames.

As already mentioned, providing intelligence to the optical layer (automatic provisioning of light paths on client demands) opens the possibility to define multi-layer traffic engineering (MTE) strategies, and offers opportunities to network operators for cost savings (both CAPEX and OPEX) [34], [35]. The implementation of ASON/GMPLS networks also opens the possibility for providing Bandwidth on Demand (BoD) services.

The following Figure 8 illustrates an exemplary network scenario in which the functionalities provided by the ASON definition can be used [39].

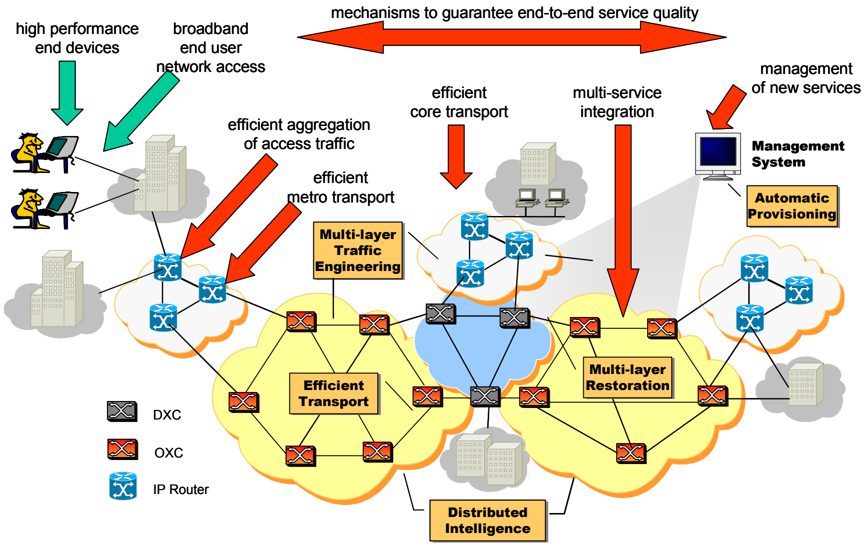


Figure 8: Reference network scenario

What ASON switched connections are needed for?

A well-designed network architecture should give to Network Operators and to Services Providers (SP) the control of their network, while providing fast and reliable connection set up. It is expected to be sufficiently generic to support different technologies, differing business needs and different distribution of functions by vendors.

The main feature of an ASON is the ability to increase/decrease the transmission capacity on demand, i.e. set up/tear down optical channels automatically (switched connections) or at least very dynamically via the OSS (soft permanent connections). This feature may reply at least to two needs:

- To cope with dynamic fluctuations of the client traffic.
- To recovery very dynamically from failures (e.g., optical fast-reroute).

The purpose of this Subsection is to show some general scenarios with clear indication who and in what cases is likely to request an automatic switched optical channel. Figure 9 and Figure 10 show two different situations where the new ASON switched connections are required [40].

Specifically, in Figure 9, two sub-networks of an individual ISP are interconnected with a permanent optical connection. The expected and the unexpected increase of the traffic carried between the sub-networks results in demands for switched optical channels.

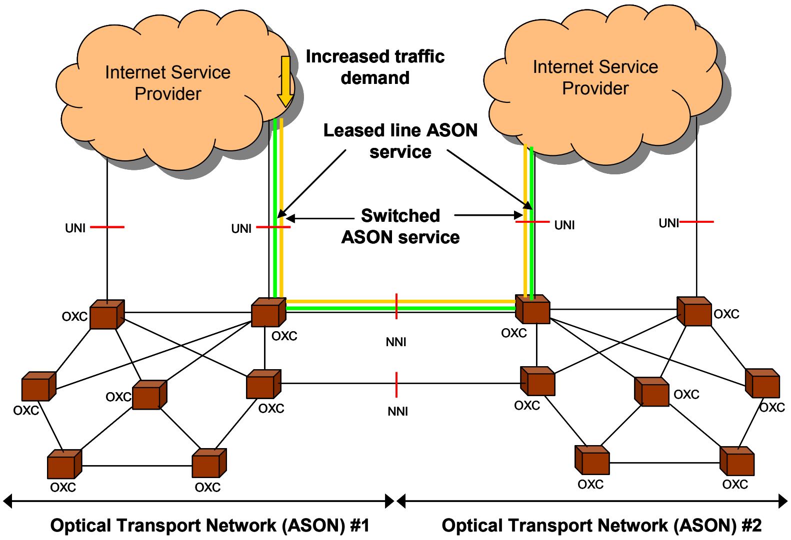


Figure 9: Switched service requested by ISP to support extra traffic

Figure 10 illustrates the other considered example. Two sub-networks of an individual ISP are interconnected with permanent optical connections. In this case, it is supposed that there are not significant changes in the traffic pattern between ISP sub-networks.

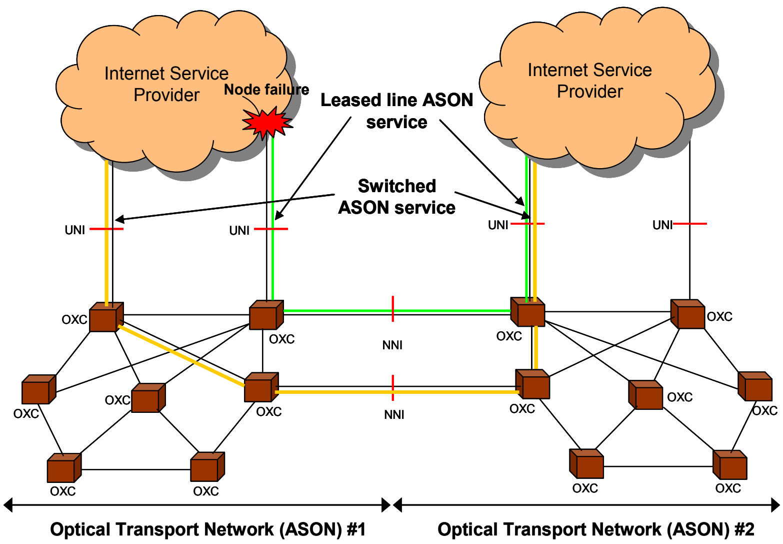


Figure 10: Switched service triggered by node failure

The node failure (link failure) triggers the optical restoration, and thus the Control Plane is requested to set up a switched optical connection to be used to recover the traffic from the failure.

When intelligent optical transport networks are taken into account, both the traffic engineering (TE) and the capacity management (CM) approaches can be considered to face with the dynamic IP traffic bandwidth demands [41].

On one hand, the TE approach ensures the maximization of the network performances both in normal and in failure conditions, trying to move "*the traffic where the bandwidth is*". As an example, it is based on centralized and/or distributed routing algorithms such as dynamic routing (e.g. time-dependent or state-dependent routing path selection) or QoS routing algorithms.

On the other hand, the CM approach provides connections to meet traffic demands minimizing the size of the network, and therefore reducing both the operational and the capital costs. It is specifically based on moving "*the bandwidth where the traffic is*".

This part of the Ph.D. Thesis deals with dynamic capacity (light paths) management procedure aiming at the optimization of the utilization of the network resources.

2.1.2 Capacity Management: Related Work

The provisioning of the connections/light paths needed to cope with a given traffic demand, is defined as the virtual topology design, which represents the set of all the light paths established in the optical network. The design of the logical topology is a very important aspect since it may lead to optimize the use of the network resources for a given traffic demand.

As an example, the virtual topology is employed by Internet Service Providers (ISPs) to efficiently connect their end equipments such as IP routers by leasing optical bandwidth from network operators who own the optical devices (i.e., fibres and optical cross-connects) [42].

Two approaches have been considered for the logical topology design, namely the off-line and the on-line approaches. The off-line approach aims at the optimization of the logical network topology according to a given and known traffic demand, while the on-line approach is applied when the future traffic demand is not known a priori (i.e. when having an unexpected traffic demand).

Concerning the off-line approach, many studies present different procedures for the optimal design of the virtual topology in a static wavelength routed scenario (no automatic bandwidth provisioning capability) and a given traffic demand [43], [44] and [45]. Moreover, a survey of such logical topology design algorithms can be found in [46].

However, the data traffic fluctuates over time, and a virtual topology optimized for a given traffic profile is not able to efficiently manage with the dynamic traffic demands. In such cases, a reconfiguration of the logical topology is needed. Different reconfiguration procedures in static wavelength routed networks, able to react to traffic changes have been proposed in [47], [48]. In these studies, the reconfiguration of the logical topology is carried out in two steps. The first step encompasses the design of the virtual topology for the new traffic demands while the second step includes the transition from the old topology to the new one. However, in these studies, the dynamics of the traffic demand are assumed to be known.

In the case of the on-line network reconfiguration, it requires two complementary steps, namely a first one consisting on deciding when a reconfiguration has to be triggered and a second one consisting on to manage the reconfiguration itself (i.e., setting up/tearing down of LSPs and/or light paths). Next, some related works referring basically to the latter one are discussed, while this part of the Thesis refers to the former issue.

In [4], an on-line algorithm to be used by ISPs to reconfigure MPLS networks is suggested. It proposes a traffic engineering system able to dynamically react to traffic changes while at the same time fulfilling QoS requirements for different classes of service. The solution consists of a hybrid routing approach, based on both off-line and on-line methods, and a bandwidth management system that handles priority, pre-emption mechanisms, and traffic rerouting in order to concurrently accommodate the largest amount of traffic and fulfil QoS requirements. More specifically, the TE system invokes an off-line procedure to achieve global optimization of path calculation, according to the expected traffic matrix, while invoking an online routing procedure to dynamically accommodate the actual traffic requests (LSPs establishment requests), which allows to react to traffic changes. This solution allows ISPs to efficiently manage different class of traffic in their MPLS networks. Therefore, in this work, the reconfiguration of MPLS networks was taken into account.

In [42], the authors propose an on-line centralized approach to be used by ISPs for the virtual-topology reconfiguration of a static WDM wide-area mesh network under dynamic traffic demand. The key idea of the approach is to adapt the underlying optical connectivity by periodically measuring the actual traffic load in the light paths, and react to the load imbalances caused by the traffic fluctuations, by either adding or deleting one or more light paths at a time. When a load imbalance occurs, it is fixed either by tearing down a light path that is lightly loaded or by setting up a new light path when congestion occurs. Once the reconfiguration is done, the rerouting of the client traffic over the new logical network topology is required, which means running the routing and signalling protocols to solve the routing and wavelength assignment (RWA) problem.

In such a way, ISPs can optimize the operational cost of their virtual topology by leasing only the appropriate amount of light paths to transport the actual traffic.

The above mentioned studies ([4] and [42]) propose solutions, which only concern with the reconfiguration of MPLS networks and static WDM networks and both of them provide to ISPs with procedure to efficiently respond to dynamic traffic demands. In other words, these studies do not take into account interworking features between the client and the transport layer. The automatic bandwidth provisioning capability provided by the new ASON/GMPLS paradigm is neither taken into account.

Providing intelligence to the optical layer opens the possibility to define multi-layer traffic engineering (MTE) strategies offering in such a way opportunities to network operators for cost savings, as well as the provisioning of new emerging services such as the Bandwidth on Demand (BoD).

The ASON/GMPLS paradigm is based on an integrated vision of the network, in which the different layers can interwork among them. This is recognized to provide better overall network performance as well as reduction of OPEX and CAPEX [34]. In such context, the application of the concepts of multi-layer traffic engineering (MTE) [49] or Integrated Traffic Engineering (ITE) concept [50] leads to significant improvements.

Different studies define multi-layer traffic engineering policies for IP over ASON scenarios. In such studies, TE actions are carried out involving both the IP (MPLS) layer and the optical layer. The aim of these on-line mechanisms is the reconfiguration of the network topology in order to optimize the network resources responding efficiently to dynamic traffic demands. These studies can be found in [30], [49] and [51].

In [30], the author defines a centralized integrated traffic engineering method based on the traffic routing stability. Incoming data traffic (i.e., LSPs) is classified as high priority, which can tolerate limited rerouting, and low priority, which can be rerouted after a timer has expired. Specifically, it consists of the design of a mechanism that reacts to traffic variations in MPLS over ASON/GMPLS networks. Such traffic variations are due to dynamic requests for LSPs establishments. The LSP are characterised by a fixed bandwidth requirement (10 Mbps), which means that it assumed that the traffic load supported by the light paths carrying the LSPs varies only due to the set up/release of LSPs. The suggested mechanism reacts to new high priority (HP) and low priority (LP) MPLS LSP requests accommodating them on light paths according to a routing-stability constraint. When a new LSP request cannot be accommodate on existing light paths (the required bandwidth does not match with the available light path bandwidth), the set up of a new light path is requested. A traffic monitoring is considered, which means that the number of LSPs allocated in each light path has to be advertised to the network nodes.

In [51], the authors define an on-line virtual topology adaptation procedure based on the actual traffic load, in MPLS over GMPLS networks. A network architecture where different MPLS networks (for different traffic classes) are built over the optical network is considered. Therefore each light path will be assigned to LSPs carrying an aggregation of traffic flows of the same traffic classes. An optimal routing policy is designed to set up and tear down LSPs and light paths (λSP) in response to new traffic demands. The aim is to optimise the accommodation of the bandwidth requests minimizing the costs involving bandwidth, switching and signalling.

In [49] a multi-layer traffic engineering strategy is defined to be used in IP/MPLS over ASON networks. The strategy is based on the dynamic reconfiguration of the logical topology of the network. Congestion experimented at IP layer can be solved by the reconfiguration of the logical topology of the network automatically setting up and tearing down switched connections in the optical layer.

All the works discussed take into account the network resource optimisation from the Internet Service Providers perspective, namely how the ISPs can reconfigure the logical topology connecting their IP routers by leasing the appropriate number of light paths from the network operators. Moreover, these MTE mechanisms react to the bandwidth requests generated from the client layer.

2.1.3 Problem addressed in this Thesis

The approach presented here is rather different. In this part of the Thesis, it is defined a procedure for the dynamic management and control of the available light paths in order to keep limited the size (in terms of number of resources) of the optical transport network. The aim is to provide, at any moment, the bandwidth required to transport through the ASON, the MPLS-LSPs already established at the client layer, avoiding congestions and under-utilisation of the light paths.

We consider that the aggregated traffic load carried by the light path fluctuates over time due to many reasons, such as the actual bandwidth (not the nominal) required by already established LSPs, the request for the establishment of new LSPs and the actual increase/decrease of the traffic carried by LSPs without a predefined maximum bandwidth.

Our procedure consists on the design of a proper capacity management/traffic engineering procedure to trigger the requests for the automatic set up and tear down of switched connections to adapt the bandwidth available at the transport layer to carry the aggregated client traffic. We assume that the light paths set up/tear down is in charge of the GMPLS routing and signalling protocols and therefore, routing and signalling issues are out of the scope of this Thesis.

This TE strategy is to be applied at the edge routers of the optical transport networks which collect the data traffic from the different client networks (i.e. Internet Services Providers) and provides to the Network Operators, who own the transport network and the access router, with a cost-effective management of the transport network resources. At the same time, it provides the client networks with a new transport service such as Bandwidth on Demand (BoD).

Specifically, Next Chapter is devoted to describe this procedure which can be classified as a multi-layer traffic engineering approach to track the fluctuations of the client traffic.