3 Capacity management in IP/MPLS over ASON/GMPLS networks

Currently there is an increasing interest of vendors, operators, *fora* and different international research projects around ASON, namely around the introduction of automatic switching capabilities in the optical transport networks. However, up to now there is not a market model which states, for example, potential customers of ASONs, potential statistics of the requests of switched connections, nor the real advantages of ASON implementation for Network Operators. Definitely, a traffic demand model for ASON is not yet defined which leaves some open issues such as:

1. The design of a proper procedure to automatically trigger demands/requests for setting up/tearing down switched connections to adapt the bandwidth available at transport layer according to the incoming client traffic fluctuations.

2. The characterization of the statistical distribution of the connection demands for the most significant clients of ASON. In particular, we refer to the Holding Time (HT) and the InterArrival Time (IAT), where the IAT is the time elapsing between two consecutive requests for the set up of switched connections while the HT is the time elapsing between the seizure and the release of a connection.

In this part of the Thesis, we concentrated on IP networks as clients of the ASON transport networks. In particular, in this Chapter we define TRIDENT, a procedure for the efficient capacity management for IP/MPLS over ASON/GMPLS networks, describing its characteristics and merits. TRIDENT is a procedure to be used by the Network Operators to dynamically manage the bandwidth available at the optical transport layer in order to track the fluctuations of the client networks in an IP/MPLS over ASON/GMPLS environment. It consists on avoiding both the over- and the under-utilization of the transport network resources (and aiming at keeping limited its size) while coping with the dynamic fluctuations of the incoming client traffic. Moreover, it is a way of implementation of a new *telco* service such as Bandwidth on Demand (BoD). However, it is worth noting that there are significant ASONs clients different from the IP clients. Therefore, in the next Section we discuss, as related work, the research activity done within the framework of the IST-1999-11387 Layers Interworking in Optical Networks (LION) project funded by the European Union, by the University of Science and Technology (AGH) [40], [52], in which the authors identified some potential customers of ASON transport services (apart from the IP clients). Moreover, they investigated the switched connection demands imposed on ASON networks by such kind of clients, focusing specifically on the HT and the IAT statistics.

3.1 Potential customers of ASON services: Related Work

This Section describes some of the potential applications, which users could benefit from the introduction of automatically switched transport services. Specifically, we discuss the banking sector, the video service delivering and the health care service.

3.1.1 Banking Sector

The most promising candidate for being ASON customer is the banking sector. Currently, banks are very important clients of telecommunications operators. They are using permanent connections or virtual private networks (VPN) for their purposes e.g., online data exchange, management and backup. They will probably maintain at least low capacity protected permanent connections but the use of high capacity switched connections would be more convenient and economical for them (especially in case of backup). Huge banks could be the first to replace traditional leased lines solutions with switched connections.

A typical structure of a bank is shown in Figure 11. It usually consists of bank headquarters (BH), dozens of branch offices (BO) and hundreds of local offices and automated teller machines. The whole system is guard against severe disasters by at least one backup centre (BC).

To determine possible demands the banking sector may impose on ASON networks, the authors made some assumptions basing on non-confidential data about Polish banks from [53], [54] and Polish official statistics [55]. They assumed that there are 70 banks in a hypothetical European country. All of them have headquarters in the capital and 35 banks have backup centres in the capital. Each bank has on average 4 branch offices in the capital and 34 in the country. It holds 420,000 customers' accounts of average size of about 250 KB. On the above assumptions, a data volume between BH and BC as well as BH and BO (105 GB and 3.1 GB respectively) was made. This, in turn, led to estimate the Holding Time and Inter Arrival Time values, which can be found in the upper part of Table 1.

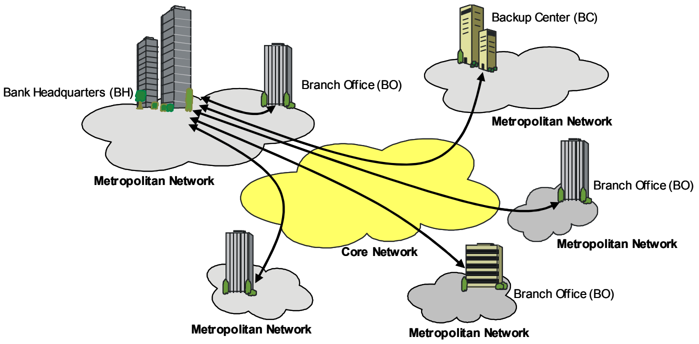


Figure 11: Structure of a typical bank

Data are sent once per month in Bank Headquarter-Backup Centre (BH-BC) case. For BH-BO connections data are sent once per day (only data that were modified during the day). Values in the Table 1 refer to 3 hours after Branch closing.

In terms of requirements, the banking sector will probably not have strong requirements on blocking probability and may accept a delay in connection set up.

3.1.2 Video delivering service

Switched connection services may be used for delivering not only data but also other kind of content (e.g. voice, video) to the customers. The chain of digital cinemas is a good example of potential customer of these services.

For years celluloid has been used as the medium for recording, storing and projecting images. Nowadays, computer workstations and high-resolution electronic video projectors are replacing conventional 35 mm film and projectors. Such system is called Digital Cinema. Digital Cinema is a system capable of delivering full motion pictures, and other audio/visual cinema-quality programs to theatres throughout the world using digital technology. Digital Cinema systems is used to distribute motion pictures which have been digitised and delivered to theatres using either physical media distribution (e.g. DVD) or digital transmission methods like fibre cable. At each showing, the digitised information is retrieved from the local storage and displayed using cinema-quality projectors. Digital Cinema ensures high quality motion picture at every showing without film degradation. Digital projector may be used for pay per view events, interactive entertainment, corporate presentations, e-commerce, distance learning and video games. Moreover, distribution of digital releases may permit studios to rapidly change distributing pattern accordingly to the market demand. Additionally, Digital Cinema systems may hamper piracy problem by worldwide movies exhibition before illegal copies become available on the market.

According to [56], 10 Digital Cinemas are placed in Europe (about 50 in the world [57]). Although, a few Digital Cinemas exist today in Europe, it may be assumed that in the near future the number of such theatres will rise. However, it is hard to estimate how many digital cinemas will operate. The number of such cinemas may vary with population, GNP and preferences of particular population.

To determine possible demands imposed on ASON by the deployment of Digital Cinemas, the authors assumed that 40 multiplex cinemas would operate in a hypothetical country. Multiplexes seem to be main client of companies distributing digital movies in the beginning. In the capital city, there will be a specialized server storing digital movies as well as 5 multiplexes will operate. The number of new movies at each multi-screen cinema depends on number of screens, popularity of already projected films, etc. But it may be assumed that, on average, every two days a new film is introduced. Moreover, it may be presumed that there is a high probability of downloading movies during eight-hour workday. It may be assumed that average size of movie file is about 80 GB for two-hour movies (on the basis of specification of equipment offered by [58]). The exact size varies depending on content, source quality, frame rate, etc. The above assumptions lead to the values of mean Inter-Arrival Time and mean Holding Time included in the central row of Table 1.

3.1.3 Health care service

Another possible client of the ASON is a health care sector. After the analysis of the sector structure and various possible tele-medicine services the need for ASON services emerges in case of tele-consulting and tele-surgery.

Some surgeries are very difficult and complicated and must be leaded by doctors of high specialization. The best specialists are usually concentrated in only a few hospitals or health centres in the country, sometimes remote from the hospital where the patient is. Transportation is expensive and takes a lot of time while in some case even single minutes decide about human life. In many cases such a surgery could be remote-controlled if appropriate tools were available. The possible solution is establishing specialist centres serving for all hospitals in the country according to the structure such as depicted in Figure 12. Since the strong centres where the best specialists are employed currently exist (e.g. in Poland) and remote surgeries occur, this idea seems to be very probable.

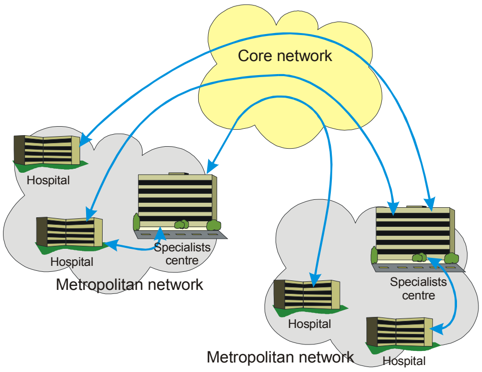


Figure 12: Structure of health care sector consisted of hospitals and specialists centres

During a tele-surgery a lot of different information must be sent between the remote centres. It encompasses one or more high-resolution video streams and on-line data from medical equipment. Hence, the need for high capacity connection emerges. Maintaining permanent connections between all hospitals and specialists centres would be too expensive. Instead, switched connections could be used.

It should be noted that cutting off the channel during the surgery might have dangerous consequences. This causes a strong demand for connection reliability (i.e. "zero" probability of connection blocking and interrupting). On the basis of Polish official statistics [55] the authors made the following assumptions, that is, there are 700 hospitals in the hypothetical European country; about 25 hospitals are located in each main city; 15 specialist centres in the country; up to 4 in some main cities. Moreover, it is assumed that: duration of a typical surgery varies from 1 to 9 hours; the required connection capacity is 155Mbit/s (one or more high-resolution video streams and on-line data from medical equipment); a hospital requires a service once per 3 days. On the above assumptions, the minimum and the maximum value for the Holding Time and the Inter-Arrival Time was obtained. These values can be found in lower row of Table 1.

		HT				**IAT**	
		2 Mbps	155 Mbps	622 Mbps	2,5 Gbps	Metro	Core
Banking sector	BH-BC	166 h	90 min	22.5 min	5.6 min	2.4 h	4.8 h
	BH-BO	3.4 h	2.6 min	40 s	10 s	4.5 s	5.1 s
Video delivering		88h	1h 8 min	17 min	4.2 min	24 min	27 min
Health care		52min	1-9 h		5.6 min	9.2 min	7.2 min

Table 1: Mean HT and mean IAT for Banking sector, Video delivering and Health care sector

In the next Subsections, the problem of the efficient transporting of the IP traffic through ASON networks is formulated and then we present the procedure we designed and evaluated within this Thesis, highlighting its characteristics and merits.

3.2 Efficient and cost-effective transport of IP traffic over ASON/GMPLS networks

Internet Protocol is the clear dominator among the layer 3 protocols. In fact, IP is expected to be the layer integrating most of the emerging video, voice and data applications. IP-based networks are likely to become the main client of ASON networks. Thus, special attention has to be paid to the case of transporting IP traffic over ASONs.

First of all, it can be considered that IP traffic varies at two different time scales, namely long-term variations (i.e. monthly, weekly) and short-term variations (i.e. seconds, hours). Moreover, IP traffic presents very fast fluctuations/peaks as well as slow fluctuations/peaks (See Figure 13).

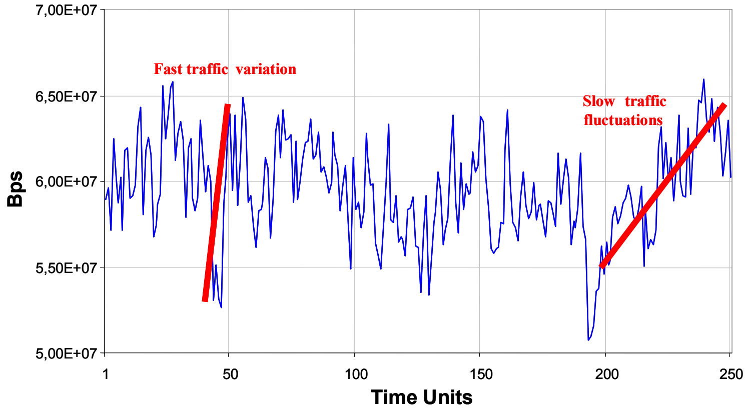


Figure 13: IP traffic fluctuations

For carrying the IP traffic, two ASON transport services can be used, namely the permanent (or soft-permanent) service to support the expected average bit rate and to cope with the IP traffic long-term variations, and the automatic switched service to cope with the short-time IP traffic fluctuations. While the permanent channels are directly set up by the NMS, the switched channels are dynamically set up/released by the CP.

It has to be highlighted that IP layer is characterized to be connectionless, while ASON/GMPLS networks provide a connection-oriented transport service. In such a context, the following questions arise: 1) when a request for the automatic set up/tear down of optical connections (light paths) has to be triggered? and 2) which are the statistical characteristics of the ASON switched connections?

These questions lead, on one hand, to the necessity to design a mechanism that triggers demands to set up/tear down connections/light paths as a function of the fluctuations of the aggregated IP traffic. The aim is to efficiently manage the capacity available in the optical transport layer to cope with the near real-time bandwidth requirements of the client traffic. On the other hand, they lead to define a suitable traffic model for the ASON dimensioning.

These two issues have been addressed in this work, the former in current Chapter and the latter in Chapter 4.

3.2.1 Triggering demand model: Definition of specifications

Concerning the above mentioned former issue, the first step in the design of this procedure consisted on evaluate the specifications it has to cope with. Basically, the clear requirements are: 1) Maximization of the bandwidth utilisation of the light paths (in order to reach TE objectives), 2) Limitation of the number of set up requests in order to avoid, on one hand, both higher layers instabilities and to excessively increase the control plane routing and signalling functions and, on the other, to obtain HT and IAT statistics compatible with the time required by the CP to establish an end-to-end switched light path and, 3) Minimization of the IP packet losses.

Thus, we carried out different studies in order to evaluate the best strategy to manage the capacity available at the optical transport layer to track the fluctuations of the incoming traffic to cope with the above mentioned specifications. In particular, this Subsection deals with the steps we carried out which allowed us to design a proper procedure.

In IP/MPLS environment, a simple LSP set up policy based on the traffic-driven approach has been proposed in [59], in which an LSP is established whenever the number of bytes forwarded within one minute exceeds a threshold. In IP over ASON environment, we use a similar approach. Specifically, we propose a procedure including a monitoring function of the client network traffic offered to the ASON, and triggering the requests for the set up/tear down of switched connections according to what results from this monitoring [52]. As an example, Figure 14 shows a possible architecture based on Traffic Engineering (TE) Servers for an IP over ASON scenario that includes the following functions:

- Traffic monitoring at IP layer.
- Signalling in the control plane, management coordination between IP and ASON.
- Establishing/releasing light paths according to the routing scheme.

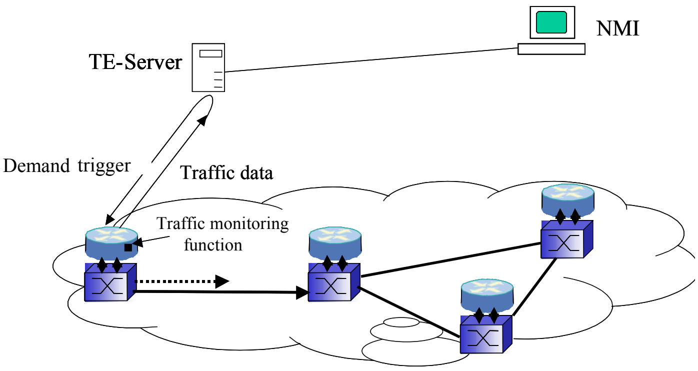


Figure 14: Possible architecture based on TE Servers for IP over ASON

The traffic monitoring function is installed at the ASON client (e.g., the “access” router of the transport network, which owns to the Network Operators), and has to be designed to monitor a parameter of the IP traffic injected in the transport network. Some examples of the monitored parameters can be the amount of the data, the link utilization or the occupancy of the electrical buffer of the router interfaces.

The monitoring function can be done by monitoring, either the instantaneous value to track even the fast variations, or an average value (and thus computed periodically) of the considered parameter. As a result of the monitoring function, node congestion due to a traffic burst/surge or under-utilization of the optical connections condition is detected. In order to do this, a threshold-based policy is used. Specifically, the reaction (triggering of a request for the set up/tear down of switched connections to cope with the burst) is produced once that monitored value goes above/below a predefined threshold. Either a single threshold or two can be used, one for setting up connections (congestion threshold) and the other for releasing them (under-utilisation threshold).

As first step, we considered the monitoring of the instantaneous fluctuations of the aggregated IP traffic from a source node (collecting the incoming traffic from the client network) towards a given destination node, and we based the request for the set up/tear down of the switched connections (SC) using a rule based on a ***static scheme*** [60], which means that the request for switched optical connections is triggered if the traffic in the link exceeds the predefined threshold. The switched optical connection is going to be torn if the traffic comes back below the threshold.

Figure 15 depicts the procedure to request the set up/tear down of switched connections (SC) using the static scheme.

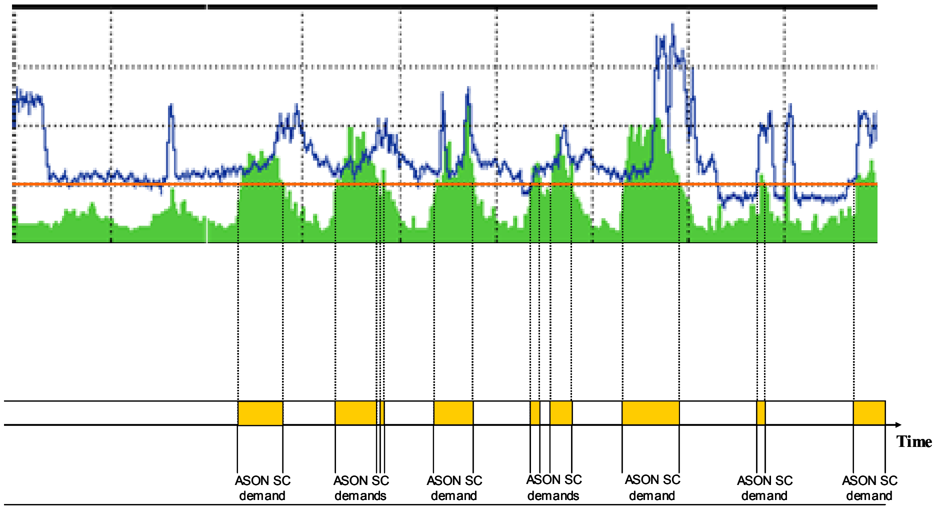
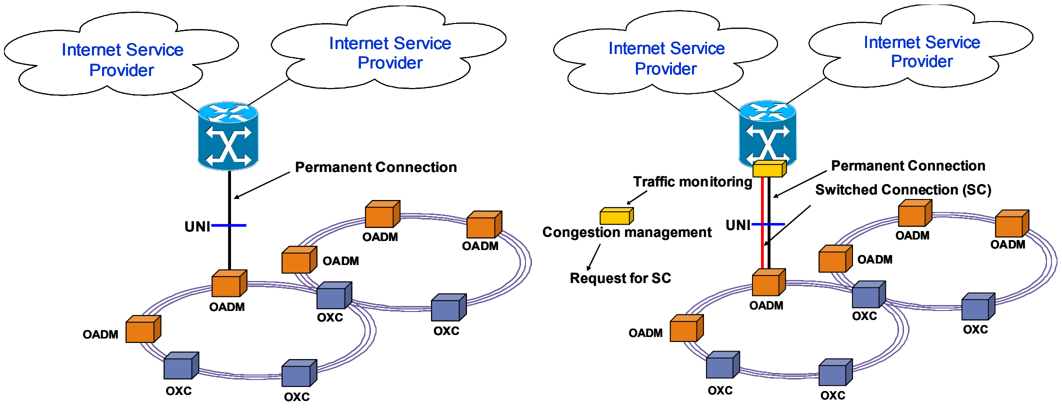


Figure 15: Triggering connection requests procedure based on the Static scheme

Figure 16 (a) and Figure 16 (b) depict how the procedure based on the monitoring of the client traffic works. For example, initially, a permanent connection/light path is established through the NMS to carry the IP traffic towards a given destination edge node (Figure 16 (a)). When a congestion situation, due to a traffic burst, is detected (the monitored parameter is higher than the congestion threshold), then the access router triggers the request to the CP for the establishment of a switched connection towards the same destination node (Figure 16 (b)). Then, some TE rules (basically Load Balancing) are applied to optimize the bandwidth utilization of the light paths.



(a) (b)

Figure 16: IP over ASON, (a) Initially conditions, (b) using SC to track the traffic burst

To evaluate the triggering request procedure using the static scheme we built a simulation model consisted of an access IP Router on top of an OXC. Since the data traffic is characterised by a self-similar nature [61], the aggregated incoming from the IP clients was modelled using a self-similar traffic pattern and according to the IP packet size distribution suggested in [62].

In the literature, several methods have been elaborated in order to generate artificial traffic traces of self-similar processes to be used as traffic model for simulation case study. A simple method consists in multiplexing *n* flows, each of them being an ON/OFF process with ON and OFF periods having a heavy-tailed distribution (e.g., Pareto distribution) [63].

Let us consider the process resulting from the multiplexing of *n* independent instances of such processes. Let $S_n(t)$ be the process obtained by counting the number of active sources at time *t*. As *n* increases, the process is asymptotically self-similar. Each ON and OFF period is Pareto-distributed. The Pareto distribution has the following probability distribution function (pdf) and mean value:

$$f(x) = \alpha \frac{k^{\alpha}}{x^{\alpha+1}} \qquad \alpha > 0 \qquad x \geq k > 0$$

$$\mathrm{E}[x] = k \frac{\alpha}{\alpha - 1} \qquad \alpha > 1$$

Traffic from a Pareto source is generated using the inverse transform:

$$X_h = \frac{k}{(r_h)^{1/\alpha}}$$

being r_h uniformly distributed between 0 and 1, and relation between the Hurst parameter (H) [61] and the alpha parameter of the Pareto distribution α is given by $H=(3-\alpha)/2$. From the mean length of the periods, the average load each source offers and thus the overall load may be derived. The advantage of this method relies on its simplicity. Its drawback is the need to choose a large value for *n*, as the property holds asymptotically.

As expected, the obtained simulation results lead to conclude that the procedure for triggering automatically set up demands based on monitoring the instantaneous variations of the IP traffic parameters may cause Control Plane instabilities [64] because it requires to set up/release connections too often (IAT and HT have very low values, in the order of ms or even lower). The same conclusions were drawn by the simulation case study in which we improved the static scheme by using a **hysteresis scheme**, on the basis of which, the request for switched optical channel is triggered if the traffic in the link exceeds the predefined threshold and this link state lasts for at least τ_{up}. The switched optical connection is going to be torn if the traffic comes back below the threshold and this link state lasts at least τ_{down}.

So then, we discarded the monitoring of the IP traffic instantaneous fluctuations to track also the fast variations moving to monitor the traffic periodically. Specifically, we used a scheme consisting of applying an Observation Window (OW). However, using a scheme based on the average traffic calculated over an OW has the strong drawback to not track the instantaneous fast variations which can highly increase the IP packets losses. Therefore, we considered a scheme which allows on one hand to monitor the incoming traffic periodically (tracking the slow variations) and on the other that allows to absorb the peaks due to the fast variations.

Such a scheme/procedure was characterised by the introduction of an electrical buffer which collects the aggregated incoming traffic to be transported towards a specific destination node (See Figure 17). In particular, the monitored parameter was the average occupancy of this electrical buffer (Average Buffer Occupancy, ABO). The procedure includes computing the average value of the BO during each OW and triggering a dynamic connection set up demand accordingly (Figure 17) [52].

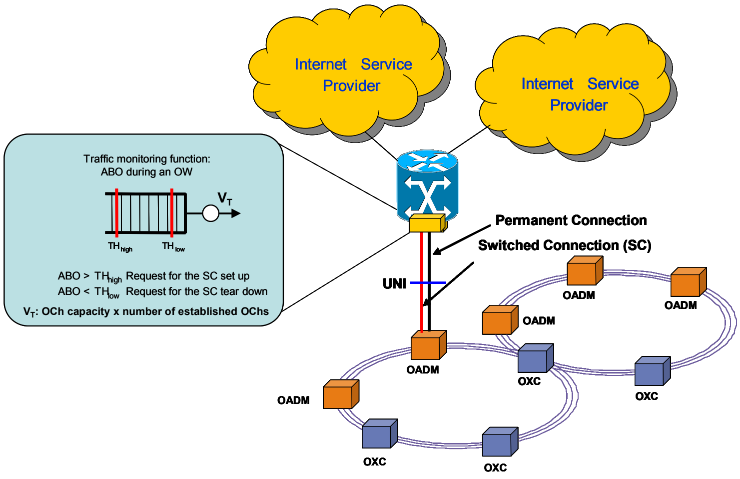


Figure 17: Capacity management based on the ABO monitoring, IP over ASON/GMPLS scenario

As above mentioned, the congestion and/or under-utilisation conditions are detected using a threshold-based policy. Specifically, two thresholds are considered, namely the congestion threshold (TH_{high}) and the under-utilisation threshold (TH_{low}). At the end of each OW, if the ABO is higher than the TH_{high}, the procedure requests to the CP the automatic establishment of a switched connection towards the same destination edge node (e.g. node Y). An example of how this procedure allows to track the traffic fluctuations is depicted in Figure 18. It presents two cases, namely the case indicated as A, in which the incoming traffic is stable and then no requests for setting up switched connections are triggered and, in the case indicated as B, the increase of the incoming traffic results on the fact that the ABO is greater than the congestion threshold and then the request for the establishment of a switched connection is triggered.

Once the switched connection is established by the CP, the aggregated traffic towards node Y is distributed among the established optical connections. The requests to the CP for the set up/tear down of the switched connections are done via UNI interface or via internal signalling, depending on the architecture of the ASON edge node. To optimise the bandwidth utilisation of the established light paths, a TE policy has to be applied, such as the Load Balancing (LB) feature, supported by current commercial IP routers [65].

On the other hand, if an under-utilization condition is detected (end of the burst), which means that ABO < TH_{low}, the procedure reacts requesting to the CP the tear down of a switched light path once the aggregated traffic to be carried towards the destination node has been reallocated to the remaining established light paths.

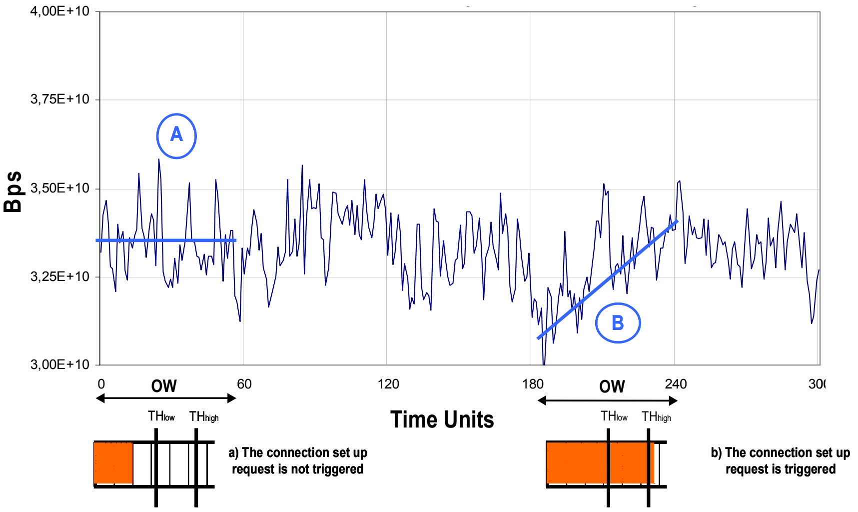


Figure 18: Capacity management based on the ABO monitoring, tracking the traffic variations

By adequately dimensioning the OW size, it is possible to fix the minimum values of IAT and HT, and make them feasible for the ASON Control Plane. Nevertheless, as shown in Figure 19, the proper dimension of the OW is a trade-off since, make it too small (case A in the Figure 19) leads to fall into the same drawbacks of the instantaneous monitoring schemes (very high number of requests for setting up/tearing down switched connections), and making it too large may lead to react behind the actual bandwidth requirements, since the triggering request decision is taken after traffic bursts appear (case B in Figure 19). This latter case may provoke very high IP packets losses due to the buffer overflow, depending on the size of the peaks.

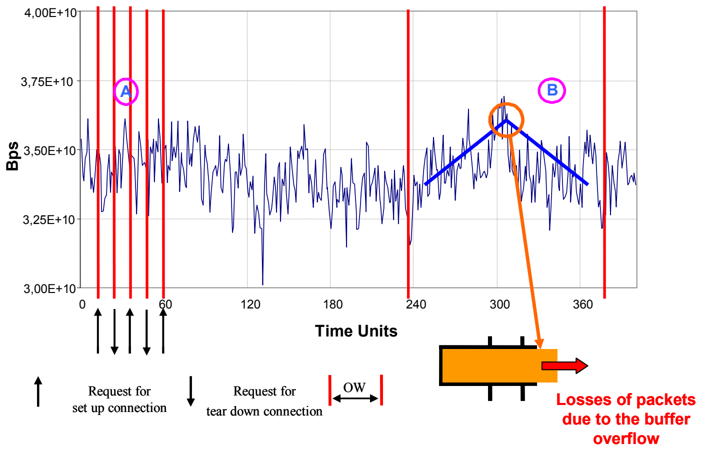


Figure 19: OW size dimensioning issue

To evaluate the feasibility and the effectiveness of such procedure, mostly to characterize the HT and IAT statistics for the switched connections, we built a simulator, in which we considered connections of 2 Mbps, the IP traffic between the couple of source and destination node taken into consideration modelled by the self-similar model above described (with an Hurst parameter, H = 0.9) with a peak rate of 140 Mbps and an average rate of 60 Mbps. It worth stressing that this is a simulation scenario to test the procedure and it is not intended as a potential real network scenario where the applicability of optical connections (DWDM) is competitive for high-capacity bandwidth requests (far above the 2 Mbps). We supposed that the size of the buffers of the router interfaces is big enough in order to avoid IP packet losses. Initially, it is assumed that at least one permanent (or soft-permanent) ASON connection is established towards the destination node. Then switched connections are set up/torn down according to the short-term evolution of that traffic by applying the above discussed procedure. A sample of the results obtained with this case study is reported in Table 2. Specifically, some results for the mean IAT and mean HT of the switched connections for different configurations for the Observation Window (OW) and the thresholds were considered.

OW (s)	$\mathbf{TH_{high}}$ (KB)	$\mathbf{TH_{low}}$ (KB)	Mean HT (min)	Mean IAT (min)
10	4	4	10.3	22.3
30	4	4	31.4	67
60	4	4	68.1	143.4
10	50	50	10.1	23
30	50	50	30.7	69
60	50	50	61	138
10	450	50	14.5	33
30	450	50	45.6	103
60	450	50	119	214

Table 2: Procedure based on monitoring the ABO, mean HT and IAT

As expected, the bigger is the OW, the higher are the mean IAT and HT. The use of two different thresholds instead of a single one produces higher values for the mean IAT and HT statistics. These results show the feasibility of the procedure since such HT and IAT times (tens or hundreds of minutes) are compatible with the time requirements for the establishment of switched connections of the control plane (i.e., of the signalling and routing protocols).

Nevertheless, as above mentioned, it is worth noting that this triggering procedure, in which the decision for requesting the setting up/tearing down of the switched connections is based on the ABO calculated periodically may produce buffer overloads which lead to high figures for IP packets losses (higher when increasing the OW). In particular, investigating the probability distribution function (pdf) of the buffer occupancy, we obtained that for the different configurations simulated the obtained packet losses figures were unacceptable for the most of the IP applications, in particular for those with stringent QoS requirements. As an example, Figure 20 shows the pdf of the buffer occupancy when $TH_{high} = TH_{low} = 4$ KB and OW = 60 s. It also depicts the probability that the buffer occupancy is greater than 512 KB and 1 MB respectively, considering these latter as reference values.

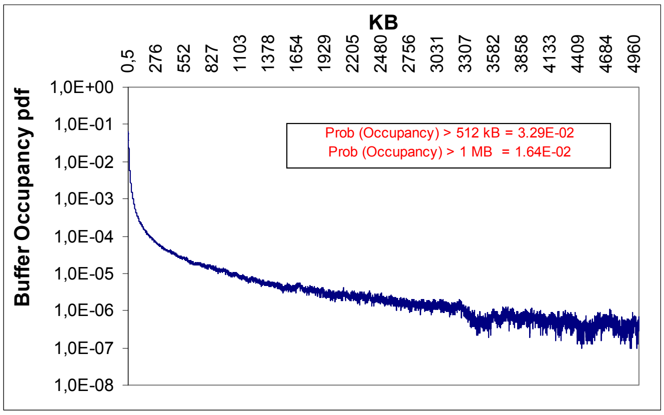


Figure 20: Probability Distribution Function of the buffer occupancy

As a consequence, based on the above discussed results, we introduced, apart from the monitoring step, a traffic prediction step. This arises from the consideration that the implementation of a prediction step advantageously allows detecting in advance the occurrence of a traffic burst, so that the control function has enough time to take the suitable decision in order to cope with the burst, reducing in this way the experimented IP packets losses. Nevertheless, using the buffer occupancy as the monitored parameter on which the decision for the set up of additional connection is based makes very hard to take benefits from the prediction step. In fact, as an example, Figure 21 shows the instantaneous buffer occupancy over time. Specifically, in Figure 20 a representative short time interval is considered.

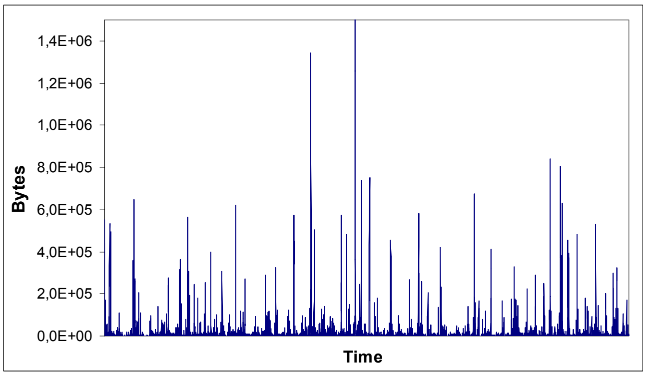


Figure 21: Instantaneous buffer occupancy over time

The strong and continue variations of the buffer occupancy over time as a consequence of the set up and/or torn down of switched connections, make to discard to implement a prediction step in the procedure described so far.

On the basis of these studies about the best approach to define a procedure to efficiently manage the bandwidth available at the optical transport layer to track the fluctuations of the client traffic, next, we propose the procedure for automatically triggering demands to set up/tear down connections in IP/MPLS over ASON/GMPLS networks.

We call this procedure TRIDENT (TRIggering DEmands mechanism for the connection set up and tear down in optical transport NeTworks based on traffic monitoring and prediction). This procedure is the matter of a Patent Application submission to the European Patent Office [66] which has been jointly authored by the Universitat Politècnica de Catalunya (UPC) and Telecom Italia Labs (TILAB), the R&D department of the Italian Network Operator Telecom Italia [67].

3.3 TRIDENT: A procedure for the automatic demand for setting up/tearing down connections in IP/MPLS over ASON/GMPLS networks

Data traffic fluctuations and network resources utilization are two opposite aspects in a circuit switching network. Thus, coping with the fluctuations of the aggregated data traffic to be transported by ASON/GMPLS networks and keeping limited the size of the transport networks, requires a proper dynamic management of the ASON switched connections.

In such a context, we define and evaluate TRIDENT, a distributed capacity management procedure for establishing switched connections to automatically track the dynamic changes of the incoming traffic. The procedure also defines traffic engineering (TE) rules required to optimise the transport network resource utilisation, reducing in this way the CAPEX of the Network Operators.

TRIDENT interworks between the client network (IP/MPLS) and the circuit switched server layer of an ASON/GMPLS network supporting permanent, soft-permanent and switched connections service for the dynamic use of transmission resources. It can be classified as a multi-layer traffic engineering approach to track the fluctuations of the client networks traffic. Figure 22 shows the scenario where to apply TRIDENT.

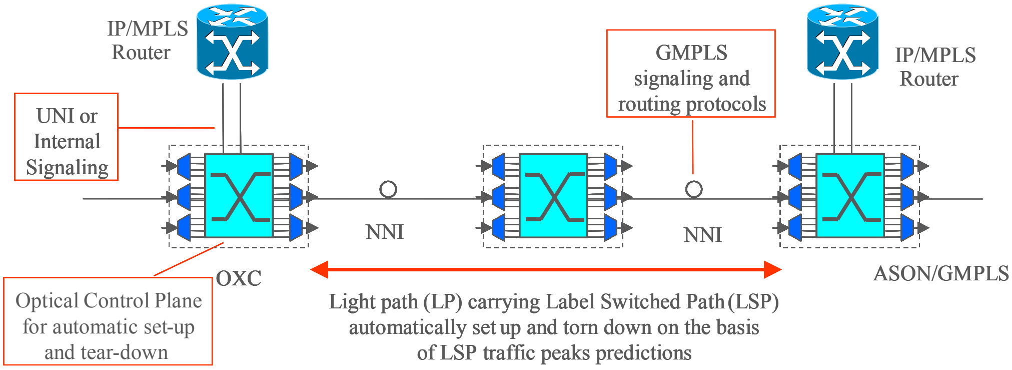


Figure 22: IP/MPLS over ASON/GMPLS network scenario

Specifically, Figure 23 depicts, as an example, an edge node integrating an IP/MPLS router and an optical switch to which TRIDENT is applied.

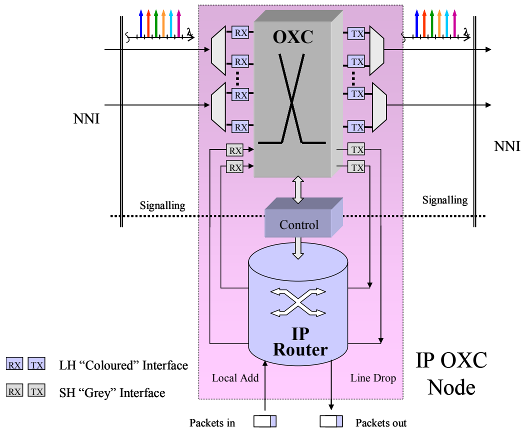


Figure 23: Peer-to-peer edge node architecture

On the basis of the growing penetration of IP-based applications which have QoS requirements (e.g., latency, jitter, packet losses), in the definition of the TRIDENT procedure we consider multiservice networks which means to take into account traffic priorities (specifically two priorities, namely high and low priority traffic). Specifically, client traffic is classified as high priority (HP) and low priority (LP) Label Switched Paths (LSPs) according to the carried applications and/or according to the established Service Level Agreements (SLA).In particular, TRIDENT implies that HP LSPs are bundled onto HP light paths and LP LPSs are bundled onto LP light paths (Figure 24). In such a way, the two types of LPs may have different routing (e.g. path length, number of hops) and survivability policies (e.g. protection, not protection, restoration, etc.) in order to meet their requirements within the transport network.

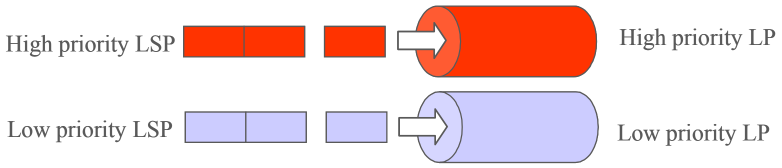


Figure 24: Switched Paths (LSPs) carried by Light Paths (LP) of the same priority

To implement the TRIDENT procedure, some interfaces of the network nodes (Layer 2 and Layer 3) are supposed to be directly allocated to high priority traffic (supporting for example a number of permanent and soft permanent/switched light paths) and some interfaces are allocated to low priority traffic (supporting for example a number of switched light paths) (Figure 25).

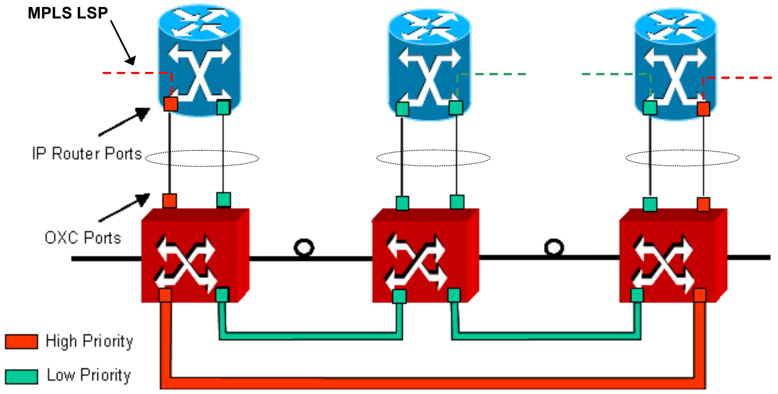


Figure 25: TRIDENT procedure, System configuration

This procedure is suggested to be implemented in the edge nodes of the IP/MPLS over ASON networks and it consists of the following steps: 1) Monitoring and short-term prediction of the data traffic entering a node at client layer, 2) Congestion management, taking benefits form the different traffic priorities, and resource utilization optimization, and 3) Automatic set up/tear down of switched optical connections.

Figure 26 depicts the interactions among the three steps which are described in detail in the next Subsections.

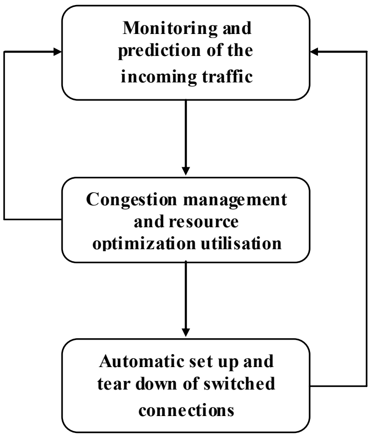


Figure 26: Steps of the TRIDENT procedure

3.3.1 Monitoring and prediction of incoming data traffic

IP traffic typically fluctuates irregularly during a day and therefore peaks of the traffic can only be identified by traffic measurements [68]. Thus, we used periodic network traffic monitoring enforced by short-trend traffic estimation in order to automatically adapt the network resources to the current network conditions in near real time, reacting to prevent possible localized congestion due to high priority traffic bursts/peaks.

According to [69], [70], [71], traffic monitoring can be performed on: Flow-based, Interface-based, Link-based, Node-based, Node-pair-based and MPLS LSP-based. Specifically, TRIDENT requires the interface-based and MPLS LSP-based traffic monitoring.

As a first option to measure the actual traffic crossing the router interfaces, the Network Management System (NMS) can be used, which means to carry out the traffic monitoring via the Simple Network Management Protocol (SNMP). It is an Internet-standard protocol for managing and control devices (e.g. routers) on IP networks. SNMP is characterised by a simple set of operations that allows the devices to be remotely managed and controlled [72]. Any sort of devices status or statistical information that can be accessed by the NMS has to be defined in a Management Information Base (MIB). On the network devices to be remotely managed, a piece of software (called *agent*) has to run. The NMS obtains the required information on the basis of the requests sent to the *agent* of the network devices. As an example, the *agent* built into the IP router will respond to the NMS requests for the variables (*objects*) defined by the MIB standard [73]. In addition, the router may have some significant new features that are worth monitoring but are not covered by any standard MIB. So, basically, the vendor defines its own MIB (proprietary MIB) that implements managed objects for the status and statistical information of their new router. For example, SNMP protocol can be used to shut down an interface of the managed device or check the speed at which an Ethernet interface is operating.

One of the most useful objects for network monitoring defined in the standard MIB is the so-called *interface* table [72]. It contains, among others, the following variables:

- *ifInOctets*: It represents the total number of octets (bytes) received by the polled interface.
- *ifOutOctets*: It represents the total number of octets (bytes) sent by the polled interface.

As already mentioned, TRIDENT relies on both the interface-based and MPLS LSP-based monitoring. We have investigated if current commercial IP/MPLS routers support MIBs able to store information about the traffic carried by the LSPs. Specifically, we found that MPLS routers from Cisco Systems implement the proprietary MIB called *mplsLsrMibCapabilityV12R0* [74], on which the *mplsInSegmentOctets* variable is defined, while we found that IP/MPLS routers from Juniper Networks support the *jnxMibs.mpls* MIB [75]. Specifically, the latter defines the variable *mplsLspOctets* which allows monitoring "*the number of octets (bytes) that have been forwarded over current LSP active path*".

On the other hand, there are currently a number of third-party measurement/monitoring products available [76]. Hence, another option is to deploy such equipments, which might have performance advantages but also introduces additional cost. As an example, very recently a novel concept for passive network monitoring of DWDM optical networks has been developed [77]. Specifically, the collection and real-time analysis of IP packet data from any one of the active 10 Gbit/s wavelength carriers on a DWDM optical network link is enabled.

The collection of the data traffic samples is carried out periodically (according to the monitoring tool) and averaged over an Observation Window (OW). Starting from these samples, traffic prediction is carried out to forecast the short-time evolution of the data traffic entering the node interfaces for the next OW. To carry out the short-term prediction of the incoming traffic to each IP/MPLS high priority router interface, the adaptive Normalized Least Mean Square (NLMS) error linear predictor ([78], [79]) is used. Since it is based on an adaptive approach, it is used as an on-line algorithm for forecasting the aggregated traffic bandwidth requirements. Generally speaking, a *k*-step linear predictor (Figure 27) is concerned with the estimation (prediction) of the next *k-th* sample of the signal $x(n)$, which means that using a linear combination of the previous values of $x(n)$, $x(n+k)$ is predicted.

A *pth*-order linear predictor has the form:

$$\hat{\chi}(n+k) = \sum_{l=0}^{p-1} w(l)x(n-l)$$

where *w(l),* for *l = 0, 1, ..., p-1* are the prediction filter coefficients.

The aim of the linear predictor is to minimize the mean square error defined as:

$$e(n) = x(n+k) - \hat{\chi}(n+k)$$

The update equation for the filter coefficient is:

$$w(n+1) = w(n) + \frac{\mu\, e(n)\, x(n)}{\|x(n)\|^2}$$

where μ is a constant called step size.

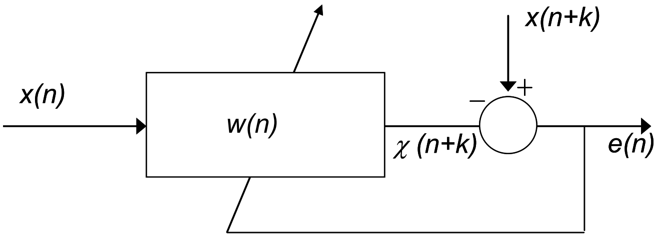


Figure 27: Adaptive linear predictor

An important advantage of using the NLMS predictor relies that is not highly sensitive to the step size. In fact, it has to be underlined that predictor design parameters should be chosen as a trade-off between low prediction error and fast convergence for prediction algorithm. Using large values for μ results in a faster convergence and quicker response to signal changes while using small μ results in slower convergence and less fluctuations after the convergence. After different simulation tests, in our implementation of the algorithm we set μ = 0.01.

In our procedure, *x(n)* represents the traffic crossing the router interfaces and the following variables are defined:

- Prediction Sample Period = τ
- Number of sample period used to predict the *k-th* future value of the traffic: *p*

Thus, at time t_0, the past *p* samples are used to predict the traffic value for at the time (t_0+k·τ). Moreover, it has to be considered that we use a linear algorithm in order to avoid increasing excessively the complexity of the procedure.

3.3.2 Congestion management and resource utilization optimization

The objective of this step is, as a result of the previous one, checking, at the end of each OW, the potential occurrence of node congestions (due to the high priority traffic) and deciding whether or not automatically trigger the request to set up/tear down switched light paths to cope with such congestions. The procedure relies on the threshold-based policy depicted in Figure 28. Comparing the predicted traffic (i.e., B_n) crossing the HP interface n with the thresholds of congestion (TH_{high}) or under-utilization (TH_{low}) (hereafter high threshold and low threshold respectively), a decision making function automatically manages the way to admit the high priority data traffic to proper connections.

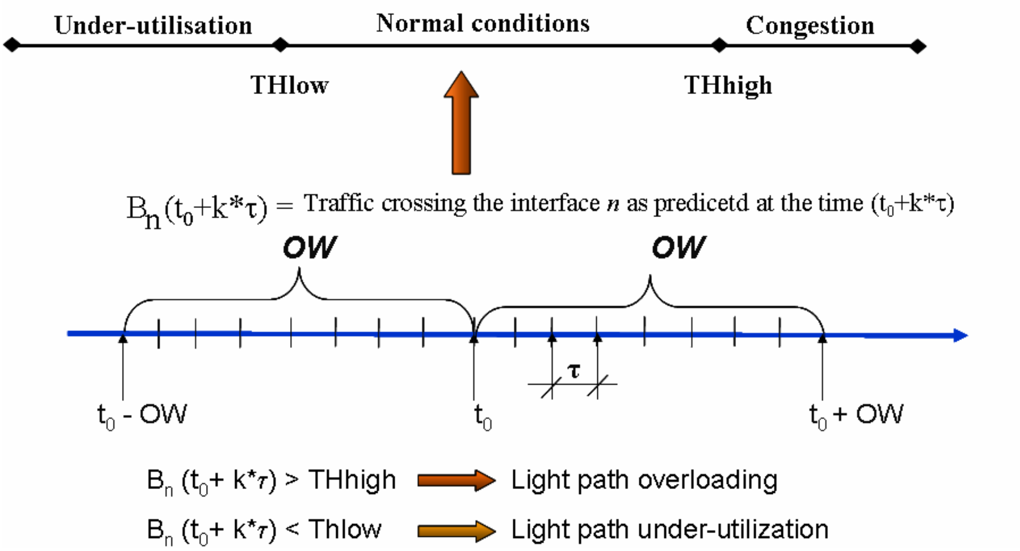


Figure 28: Threshold-based policy for congestion management and resource utilization optimization

Figure 29 and Figure 30 depict an example of how the procedure works. Initially one router interface is allocated to HP traffic (i.e. it supports a permanent HP light path) and the other router interface is allocated to LP traffic (supporting a LP light path).

When high priority traffic surges are predicted on the permanent connection (i.e., B_n higher than the high threshold), the client requests some network resources to the server layer, even if previously dedicated to low priority traffic, to be torn down in order to make them available for the high priority traffic.

The node interface made available at the server layer is used for setting up HP switched light paths to accommodate the traffic surges, thus avoiding the network congestion (Figure 30).

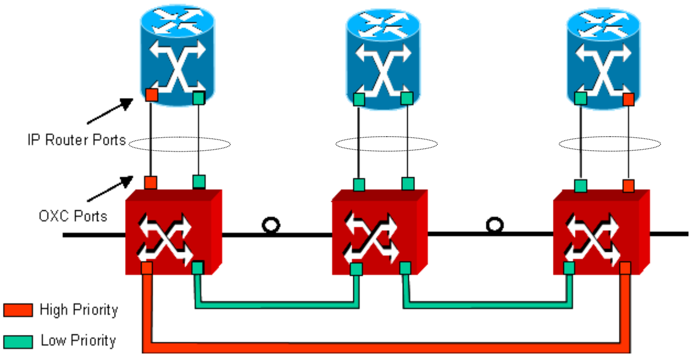


Figure 29:IP/MPLS over ASON/GMPLS network scenario with the logical LP and HP optical connections, initial conditions

The detection of both the over- and under-utilisation of the light paths relies on the thresholds. The election of the low and the high thresholds value has to be the result of the compromise among the higher layers stability as well as the routing and signalling cost functions (i.e. it has to be avoided to set up/tear down connections too often), the packets lost at the high priority router interfaces due to the sudden increases of the HP traffic (hereafter Packet Loss Rate, PLR), which are equipped with limited buffers, and the bandwidth utilization of the optical connections.

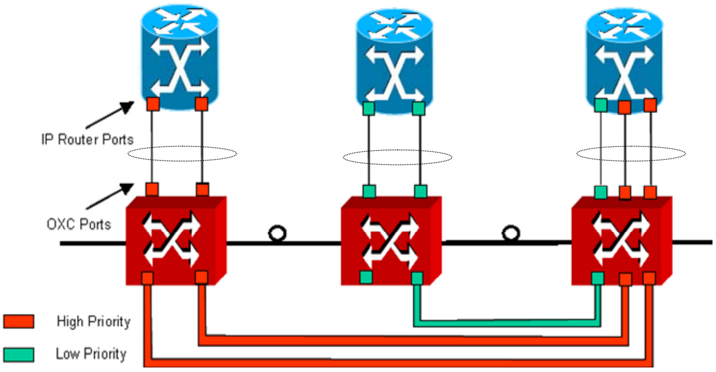


Figure 30: IP/MPLS over ASON/GMPLS network scenario with the logical LP and HP optical connections, conditions after tracking the HP traffic surges

Once the requested switched light path is established by the control plane, the predicted high priority traffic is then accommodated into the new light path and traffic engineering rules are applied to optimize the LSPs allocation in order to increase the bandwidth utilization of the light paths. When the traffic surge expires (B_n lower than the low threshold), the HP switched light path previously allocated is torn down and the network resources are restored to the initial conditions.

Figure 31 shows the pseudo-code for the procedure to handle an HP traffic burst on an HP interface. When the traffic surges expire (the predicted traffic on the HP permanent light path crosses the low threshold) the switched HP light path previously allocated is torn down and the network resources are restored to the initial conditions. Figure 32 shows the pseudo-code for the procedure which handles the tear down of an HP light path according to the end of the HP traffic burst.

The third part of this Thesis includes the description of TRIDENT procedure in detail, including the TE rules designed to optimise the bandwidth utilization of the light paths.

```
Input: monitoring of the traffic crossing the interface n, $B_n$

Output: Automatic triggering of the request for the set up/tear down of switched optical
connections

Algorithm:

At the end of each OW, on the interface n:

    While ($B_n$ > High Threshold)
        if (other HP light path towards the same destination exists (t))
            while (($B_t$ < High Threshold)&($B_n$ > High Threshold)
                1. Tag of the LSPs to be rerouted for load balancing
                2. Update of $B_t$ and $B_n$
        endif

        if ($B_n$ <= High Threshold)
            reroute of the tagged LSPs to the light path supported by t
        else

            1.  Request for the tear down of LP light path on interface t
            2.  Triggering of the request for the set up of a HP light path
                on interface t
                if (GMPLS signalling OK)
                    While ($B_n$ > High Threshold)
                        Rerouted of the LSPs for load balancing
                    endwhile
                Else
                    Reroute of the tagged LSPs
```

Figure 31: TRIDENT procedure, handling HP traffic burst at HP interface *n*

```
Input: $B_n$, $B_t$

Output: Triggering the request for the set-up/tear down of switched optical connections

Algorithm:

At the end of each OW, on the interface n:

    if ($B_n$ < Low Threshold)
        while (($B_t$ > 0) & ($B_n$ < High Threshold))
            1. Tag of the IP/MPLS traffic to be rerouted on the HP light path
               supported by the router interface n
            2. update $B_n$ and $B_t$
        endwhile
        if ($B_t$ = 0)
            1. Reroute of the tagged IP/MPLS traffic
            2. Tear down of HP light path supported by router interface t
            3. Triggering request for the set up of LP light path on router
               interface t

    endif
```

Figure 32: TRIDENT procedure, handling the end of the HP traffic burst on HP interface *n*

3.3.3 Automatic Set up/Tear down of switched connections

The automatic set up/tear down of the switched connections is done via the Control Plane (CP) and Network-Node Interface (NNI) signalling [80], [18]. Figure 33 depicts an example of switched light path establishment through the UNI and NNI interfaces.

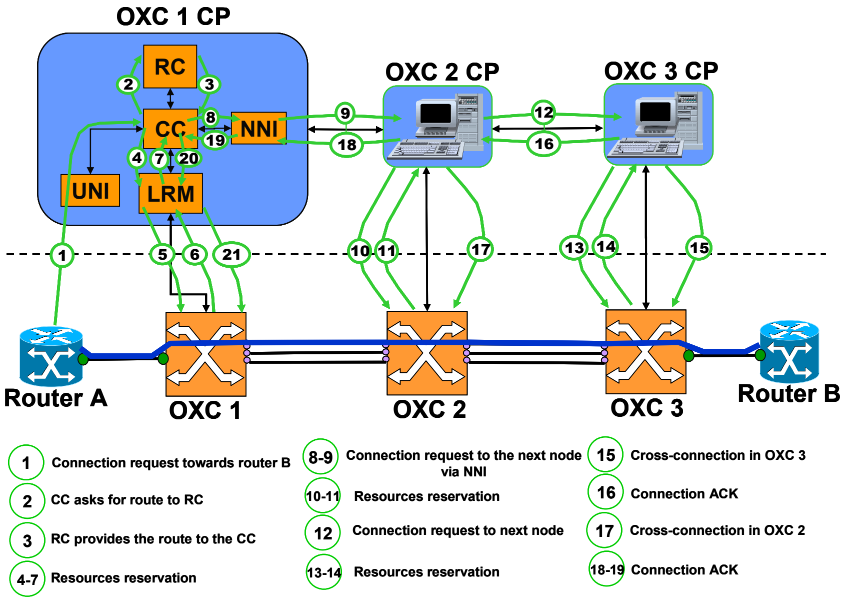


Figure 33: Example of connection establishment via UNI and NNI interfaces

Figure 34 (a) represents the block diagram of the Optical Control Plane for setting up/tearing down switched light paths in ASON/GMPLS-based nodes. To achieve that, a light path is identified by appropriate information such as source and destination node Identifier (ID), port IDs, light path ID and payload type.

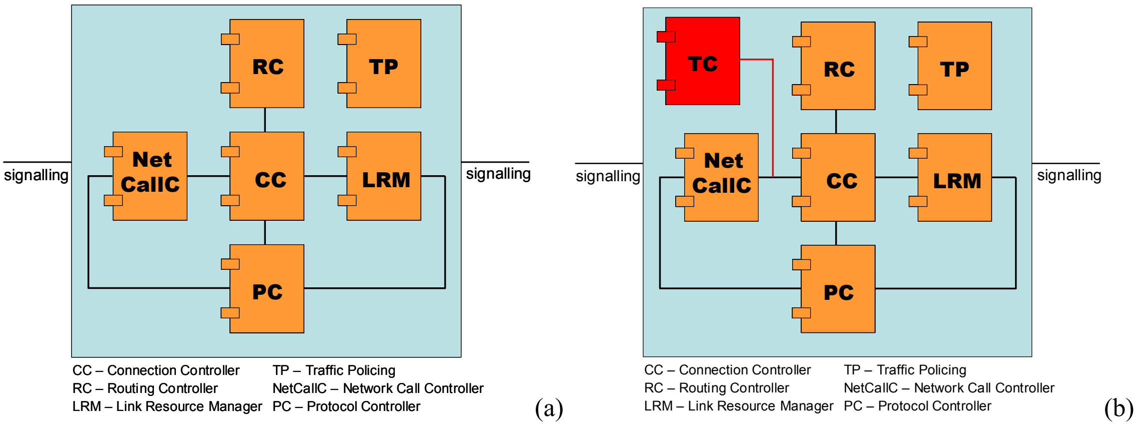


Figure 34: a) Optical Control Plane for setting up/tearing down switched light paths in an ASON/GMPLS, b) TRIDENT procedure: adding the Traffic Control (TC) component

The procedure requires the introduction of a Traffic Control (TC) component in the Control Plane of the switched transport network (Figure 34 (b)). The TC component is responsible for the collection of the raw data on the router interface, elaborating these data to predict the traffic trend and then making a decision whether or not requesting (e.g. via UNI or internal signalling) to the Connection Controller (CC) of the Control Plane, the set up/tear down of a switched connection.

3.3.4 Techno-economic advantages of the TRIDENT procedure implementation

This Section is devoted to highlight potential benefits obtained through the implementation of the TRIDENT procedure. It is designed as a cost-effective solution for network operators to transport different classes of traffic (i.e. high and low priority traffic). On the other hand, it allows the optimized utilization of the network resources according to the typical daily data traffic fluctuations as well as unexpected traffic variations due for example to equipment failures or unexpected traffic burst. Specifically, it avoids dimensioning the network resources destined to a certain class of traffic to cope with the peaks of that traffic class. Specifically, Figure 35 shows that if C is the capacity of a light path, then the number of permanent light paths potentially required in a static network to account for the peaks (B_{max}) of high priority traffic is $N = B_{max}/C$ (e.g., in At2). The result of such kind of transport network dimensioning is the no-optimal bandwidth utilization of the N light paths according to the daily traffic evolution. Contrarily, implementing the TRIDENT procedure, only $P = B_{nor}/C$ permanent light paths (for example set up by the NMS) are constantly used. In such a way, there are other additional $S = N\text{-}P = (B_{max}\text{-}B_{nor})/C$ light paths (switched connections) to cope with HP traffic peaks on the basis of periodical traffic monitoring and short-time prediction. Such light paths can be used to carry low priority traffic in absence of high priority traffic bursts or used for fast restoration in case of equipments failure.

Therefore, according to Figure 35:

- During At1: P light paths are carrying HP traffic whilst S light paths are carrying LP traffic
- During At2: N light paths are carrying HP traffic (after dropping the interface for LP traffic)
- During At3: P light paths are carrying HP traffic whilst S light paths are carrying LP traffic

For a given number of interfaces (N), the procedure allows to handle HP traffic peaks and at the same time to carry $(B_{max}-B_{nor})$*(At1+At2) low priority data traffic (i.e. when there are no HP traffic peaks).

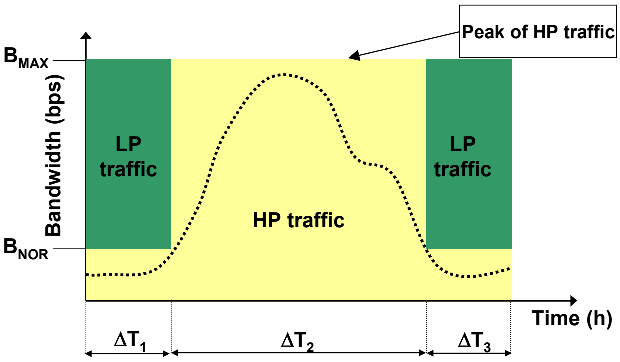


Figure 35: Basic techno-economic considerations

Another advantage provided by the procedure is that low priority traffic is transported only by low priority optical switched connections thus reserving high priority resources for high priority traffic requests. This way helps on guarantee the QoS parameters such as delay, jitter and PLR required by the HP applications.

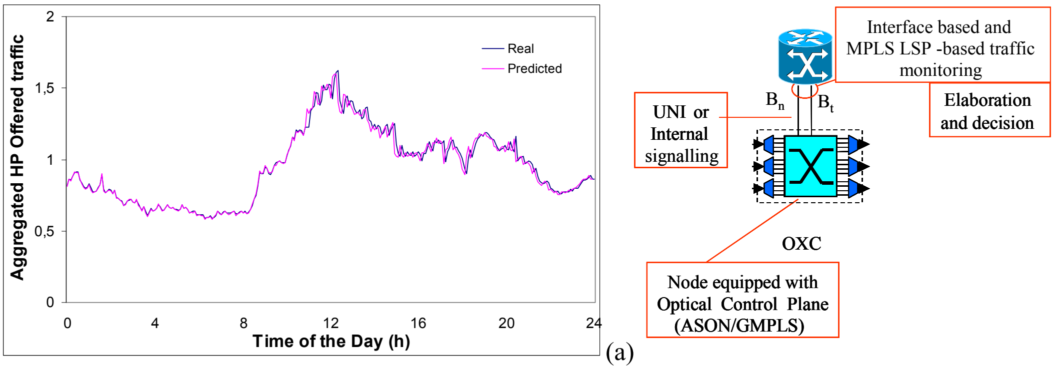
3.3.5 TRIDENT procedure: Performance Evaluation

Simulation case studies were carried out to evaluate the performance as well as the effectiveness of the procedure to handle high priority traffic surges incoming to the router interfaces tagged as HP. The simulated network was composed by IP/MPLS edge routers connected through a meshed ASON/GMPLS transport network.

Firstly, two case studies were carried out. The first one aimed at obtaining the number of the high priority light paths required to carry a certain high priority traffic pattern. In this first case study, the influence of the different parameters of the procedure on its performance was also evaluated. Specifically, we evaluated the influence of the high and the low threshold values as well as of the size of the Observation Window (OW). The second case study aimed at illustrating the effectiveness of the procedure in case of unexpected traffic surges, showing how it allows to promptly react to the unexpected fluctuations of the client traffic diverting LP network resources to cope with the surges.

The simulation results hereby reported refer to the HP light paths established between a couple of nodes (source-observed sink), according to a given daily HP traffic pattern between the two nodes. Focusing specifically on the first case study, Figure 36 (a) shows the daily HP traffic profile (normalized to the router interfaces capacity and averaged over 5 minutes) between the two nodes. In order to test the procedure with real daily traffic profiles, it has to be underlined that the traffic pattern we used in our simulation studies has been extracted from the traffic monitoring of the Catalan R&D Network (*Anella Cientifica*). Specifically, the one-day long traffic profile of Figure 36 (a) was extracted from the real trace obtained on September 22, 2003.

By applying the TRIDENT procedure, the monitoring and prediction of the traffic crossing the router interfaces is carried out periodically during the OWs. At the end of every OW, the set up or the tear down requests are triggered on the basis of the predicted traffic for the next OW, as the result of applying the NLMS prediction algorithm described in Section 3.3.1. In particular, for the prediction algorithm the following parameters were used: $p = 12$, $k = 3$ and $\tau = OW/3$. Figure 36 (a) also depict the predicted traffic resulting form the application of the NLMS algorithm. It was assumed that each router interface is equipped with buffer which size was set to 1 Mbytes.



(a) (b)

Figure 36: (a) Daily HP IP/MPLS traffic profile between the source and the destination nodes, (b) Source node at which the procedure is applied

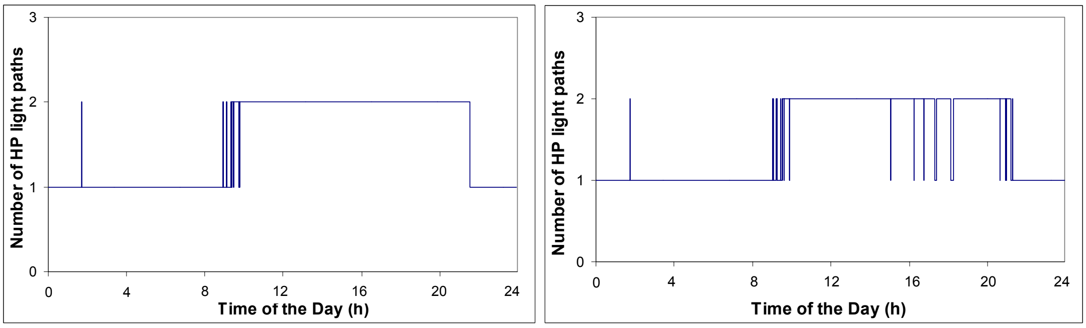
Figure 36 (b) shows the source node at which the procedure is applied. It consists of an IP/MPLS router which represents the “access” router collecting all the incoming traffic from different clients (i.e. ISPs) of the transport networks and an OXC.

Initially, one high priority router interface (supporting a high priority permanent connection) is allocated to HP traffic towards the observed sink node, whilst the remaining ones are allocated to HP and LP traffic towards other sink nodes.

Figure 37 depicts the number of established HP light paths versus time, which are used to transport the HP traffic of Figure 36 (a) between the source and observed sink node; we set the high threshold (TH_{high}) to 95% of the interface capacity while the low threshold (TH_{low}) was set to 40% (Figure 37 (a)) and 60% (Figure 37 (b) respectively. Observation Windows of 1 minute long were used. It can be observed that the number of HP light paths established between the source-sink nodes under simulation dynamically rises and falls following the HP traffic dynamics. If we had used the static dimensioning (i.e. over-provisioning approach), two HP light paths would have been used during all the simulated time, according to the client traffic peak. By applying the suggested procedure, the second interface is used to set up the second HP light path only when the permanent connection is not able to carry the aggregated HP traffic; otherwise it can be used, for example, to provide new potential services (e.g. dynamic connections for Storage) connecting the edge router towards other destination nodes. This means that, by applying the TRIDENT procedure, there is some additional capacity available in the network with the same number of network resources.

As stated above, extensive simulations have been carried out to evaluate the impact on the performance of the procedure of the different parameters characterizing the procedure itself. Firstly, it has to be highlighted that the applied thresholds policy constitutes a compromise taking care of PLR and the bandwidth utilization of the optical connections/light paths. Secondly, it has to be specially avoided to request to set up/tear down connections too often. This is due, basically, on one hand, to avoid potential instability at the higher layers and, on the other hand, to avoid to excessively increase the cost of the routing and the signalling functions of the control plane.

Figure 37 shows the effect of the increase of the low threshold value. The mean number of the light paths required to carry the high priority traffic when the low threshold is set to 60% of the interface capacity is lower than the case of fixing it to the 40%. This is due to the fact that the higher the low threshold is, the earlier the procedure starts to restore the initial conditions and therefore the lower is the mean holding time of the switched connection.



(a) (b)

Figure 37: Number of light paths needed to carry the high priority IP/MPLS traffic, a) TH_{low} = 40% of the interface capacity, b) TH_{low} = 60% of the interface capacity

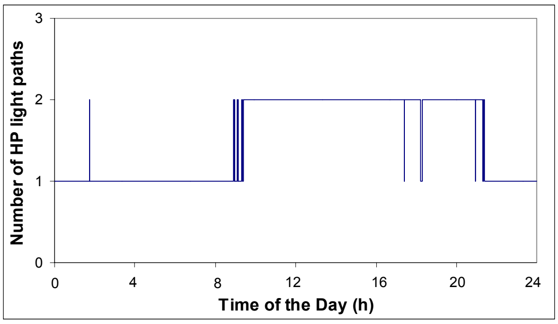
The low threshold also influences the bandwidth utilization of the permanent connection as well as the experimented PLR. In fact, to restore the initial conditions (i.e. to request to the Control Plane the tear down of the switched connection), the IP/MPLS traffic that is being carried by the high priority switched connections has to be switched back to the permanent connection. Therefore, the higher the low threshold is, the higher is the bandwidth utilization of the permanent channel (it is shown in Table 3). Nevertheless, as pointed out above, the number of requests for the set up/tear down of the switched connection is higher, increasing thus, the routing and signalling cost functions. Besides, the higher the low threshold is, the higher is the PLR (Table 3).

TH$_{high}$ = 95%	**Mean Bandwidth utilization**	**PLR**	**TH$_{low}$ = 60%**	**Mean Bandwidth utilization**	**PLR**
TH$_{low}$ (%)			**TH$_{high}$ (%)**		
40	68%	4.79E-05	90	74%	3.5E-05
60	77%	0.97E-04	95	77%	0.97E-04
80	78%	1.0E-04	97	78%	1.7E-04

Table 3: Impact of the high and low threshold

As a solution to avoid requesting the setting up/tearing down of the switched connection too often, we define a conservative approach. It consists on holding the switched connection even if not strictly required, which means that the request for the tear down of the HP switched connection is triggered only when the under-utilization condition is produced for a certain number of consecutive (*n*) OWs. As an example, Figure 38 shows the light paths established to carry the client traffic by applying the conservative approach with $n = 3$. The result is referred to the case in which the high threshold is set to 95% and the low threshold is set to 60% of the router interfaces capacity.

The mean number of requested light paths is lower than the case without the conservative approach. Also, in this case, the PLR is lower. Nevertheless, holding the switched connection implies that the bandwidth utilization of the permanent connection is lower.

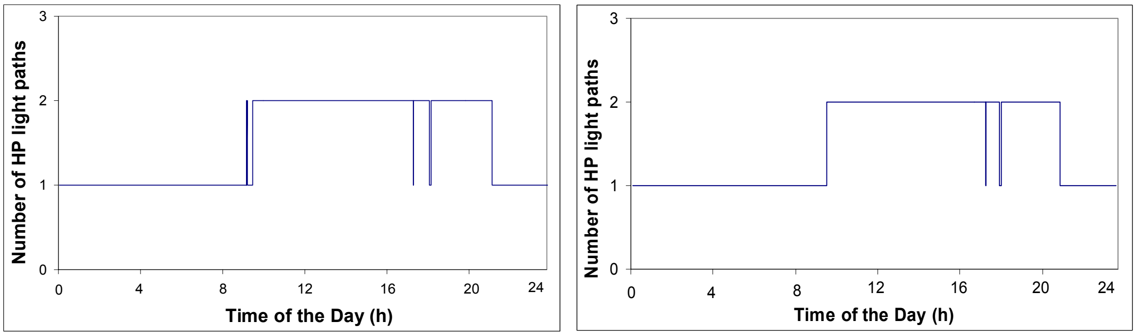


TH$_{low}$ = 60% Tear-down counter = 3	**Bandwidth utilization**	**PLR**
TH$_{high}$ (%)		
95	73%	4.4E-05
97	77%	1.1E-04

(a) (b)

Figure 38: Number of light paths using the conservative approach, b) Permanent connection mean bandwidth utilization and experimented PLR

On the other hand, to reduce the number of requests for the set up/tear down of the switched connection, another approach is based on increasing the size of the OWs. As an example, Figure 39 shows the number of the light paths established to carry the HP traffic when OWs of 3 and 5 minutes long respectively were considered. In fact, in this case, the number of requests for the set up/tear down of switched connections is lower than the previous cases (i.e., OW of 1 minute).



(a) (b)

Figure 39: Number of light paths increasing the OW, a) OW = 3 min, b) OW = 5 min

However, with the increasing of the OW size, the experimented PLR is higher (See Table 4). Basically, this is due to the fact that the higher the OW is, the worse is the prediction of the traffic crossing the router interface.

TH_{low} = 60% TH_{high} = 95% OW (min)	**PLR**
1	1.0 E-04
3	2.38E-04
5	3.4E-04

Table 4: PLR when increasing the OW

However, by implementing the prediction step the PLR is lower with respect to the case without prediction. In fact, in all the simulated configurations, using the traffic prediction provides better PLR figures than the cases without prediction. As an example, the Table 5 shows the comparison when using OW of 3 and 5 minutes respectively, and setting the TH_{high} and TH_{low} to 95% and 60% of the interface capacity respectively.

TH_{low} = 60% TH_{high} = 95%	**PLR**	
OW (min)	With prediction	Without prediction
3	2.38E-04	2.65E-04
5	3.4E-04	1.46E-03

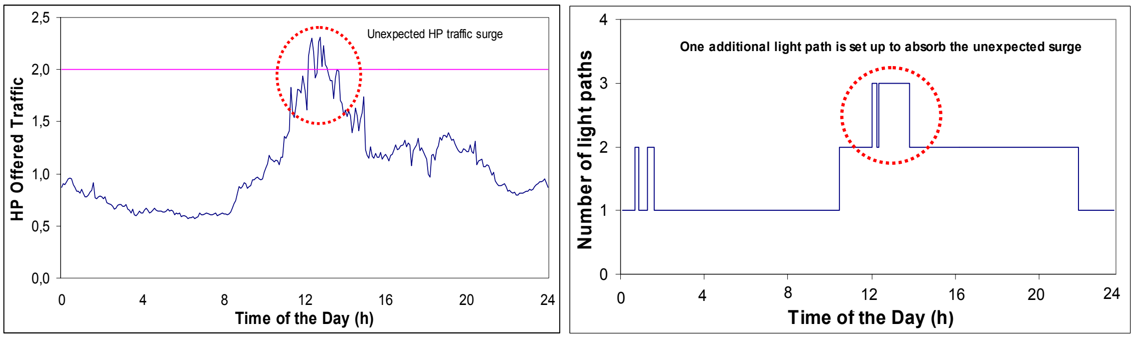
Table 5: Improving PLR by using prediction step

We also evaluated the influence of the high threshold when maintaining fixed the low threshold. It influences both the bandwidth utilization of the permanent connection and the PLR. Specifically, as depicted in Table 3, the higher the high threshold is, the higher is the bandwidth utilization. This is because, when the high threshold is increased, the congestion condition, and consequent request for the HP switched connection, is detected when the actual bandwidth utilization of the permanent connection is higher.

Nevertheless, increasing the high threshold implies that there are more packets lost at the router interfaces are as a consequence of the sudden increases of the HP traffic. In fact, as shown in Table 3, the experimented PLR is higher. On the other hand, the thresholds value can be can be dynamically changed on the basis of the actual bandwidth utilisation of the light paths and/or on the basis of the actual PLR. For example, we can introduce additional Updating Window (UW), much larger than the OW (e.g., UW = $m \cdot$OW). Sizing properly the UW, the thresholds values can be dynamically modified on the basis of the bandwidth utilisation and PLR during the previous UW.

The second case study aimed at evaluating the effectiveness of the procedure in case of unexpected traffic bursts. The HP traffic profile showed in Figure 40 (a) is the daily traffic profile between the two nodes. If compared with the previous traffic profile, it is characterized by an unexpected traffic burst. The traffic volume to be transported is higher than the expected one. In this case the procedure, contrarily to both the over-provisioning and the scheduled approach, is able to promptly react to the traffic burst adapting the bandwidth to the traffic that has to be carried.

The plot of Figure 40 (b) was obtained with the high threshold set to 95% while the low threshold was set to 60% of the router interface capacity. OW of 5 minutes long and the conservative approach with $n = 3$ were used.



(a) (b)

Figure 40: a) HP client traffic with unexpected burst/surge, b) Number of HP light paths needed

As stated above, extensive simulations were carried out to test the procedure considering different values for the parameters of the procedure itself. The following Table 6 summarizes the results obtained when OW 1 minute long was considered. Firstly, the TH_{high} is fixed to 95% of the interface capacity while varying the TH_{low} the number of set up requests, the percentage of time the additional HP light path is required and the mean HT and IAT for the switched connection were obtained. Table 6 shows that the percentage of time (calculated over the simulation time, i.e., 24 hours) the HP switched connection is required, is about the 50% (about 12 hours). This means, that during about half a day, the second interface can be used to carry different traffic (e.g. LP) traffic or to provide new emerging services such as storage service. On the other hand, the obtained mean HT and IAT are compatible with the time required to provide a switched connections by the control plane.

OW = 1min **TH_{high}= 95%** TH_{low} (%)	Number of set up requests	Time percentage of using the SC[1]	Mean Holding Time (min)	Mean InterArrival Time (min)
40	11	51%	61	121
60	21	48%	34.45	69.57
80	21	47.2%	32.38	72.35

OW = 1 min, **TH_{low} = 60%** TH_{high} (%)	Number of set up requests	Time percentage of using the SC[1]	Mean Holding Time (min)	Mean InterArrival Time (min)
90	19	52.5%	39.8	76.79
95	21	48%	34.45	69.57
97	25	46.2%	27	58.64

[1] calculated over the simulated time

Table 6: OW = 1 min, summary of simulation results

In the case of maintaining fixed the TH_{low} and increasing the TH_{high} threshold, the effect is to increase the number of set up requests. This due to the fact that the higher is the TH_{high} the higher is the amount of traffic switched back from the switched light path when the tear down procedure is activated. Then, the probability to cross again the TH_{high} on the permanent connection is higher.

The designed procedure does not require the knowledge of the future traffic pattern. It is an adaptive mechanism to efficiently manage the bandwidth available at the optical level and able to provide in near-real time the bandwidth required by the LSPs established at the client layer. Therefore, as additional simulation case study, we applied the designed procedure also to different traffic profile extracted from the Catalan Academic Network (CAN). Specifically, the one-day long traffic profile was extracted from the real trace obtained on May 13th 2004. The simulation results hereby reported refer to the HP light paths established between the same couple of nodes, according to the daily HP traffic pattern between the two nodes. Initially, one high priority router interface (supporting a HP permanent connection) is allocated to HP traffic towards the observed sink node, whilst the remaining ones are allocated to HP and LP traffic towards other sink nodes. As a sample of the obtained results, the following Figures and Tables refer to the number of light paths used to carry the considered HP traffic profile. First of all, it can be observed that in this case, the HP traffic volume between the two observed nodes is higher than the previous case. Figure 41 report the number of HP light paths established in the case of using OW 5 minutes long, TH_{high} = 95% and TH_{low} = 60% of the interface capacity, and by applying the above described conservative approach with *n* = 1 and *n* = 7 respectively. First of all, the number of HP light paths established between the source-sink nodes under simulation dynamically rises and falls following the HP traffic dynamics. The switched connections are used only when strictly required. By increasing the parameter *n*, the number of set up requests decreases making the procedure feasible with the CP requirements.

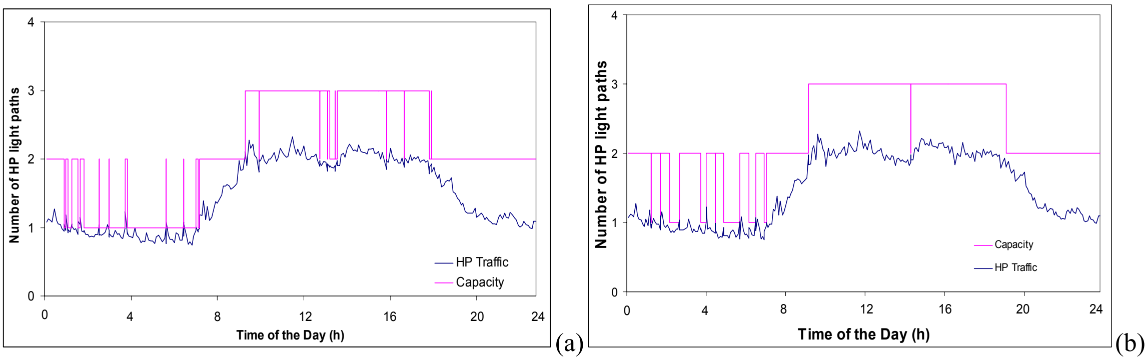


Figure 41: Number of HP light paths, OW = 5 min, conservative approach; (a) n = 1, (b) n =7

The following Table 7 and Table 8 summarize the different simulations results we obtained. OWs of 3 and 5 minutes long were considered respectively. Specifically, it is reported the percentage of time over the simulated one in which the switched connections are required to transport the HP traffic, the mean HT and IAT for the switched light paths and the PLR.

OW = 3 min, TH_{high} = 95 % TH_{low} = 60 %	Number of set up requests	Time percentage of using the first SC^1	Time percentage of using the second SC^1	PLR
n = 0	41	76.87%	33.3%	2.4E-03
n = 3	35	82.1%	35.62%	2.16E-03
n = 6	19	90.62%	38.12%	1.59E-03

OW = 3 min, TH_{high} = 95 % TH_{low} = 60 %	Mean Holding Time for the first SC^1 (min)	Mean Holding Time for the second SC^1 (min)	Mean IAT for the first SC^1 (min)	Mean IAT for the second SC^1 (min)
n = 0	41	32.2	22.44	41
n = 3	56.28	39.46	23.4	50
n = 6	93.21	91.5	39.7	117

Table 7: Summary of results using the conservative approach, OW = 3 min

In particular, we consider the impact of the conservative approach, since we compare the different figures considering different values (*n*) of the held OW before triggering the request for the tear down of the connections.

OW = 5 min, **TH_{high} = 95 %** **TH_{low} = 60 %**	Number of set up requests	Time percentage of using the first SC[1]	Time percentage of using the second SC[1]	PLR
n = 0	27	78.47%	35.07%	2.46E-03
n = 3	14	84.02%	40.62%	1.92E-03
n = 5	12	87.5%	39.58%	1.91E-03
n = 7	9	89.23%	39.58%	1.6E-03

OW = 5 min, **TH_{high} = 95 %** **TH_{low} = 60 %**	Holding Time for the first SC[1] (min)	Holding Time for the second SC[1] (min)	IAT for the first SC[1] (min)	IAT for the second SC[1] (min)
n = 0	66.47	45.90	37.81	60
n = 3	108	600	47.72	-
n = 5	140	142	63.75	195
n = 7	142.77	285	63.75	310

Table 8: Summary of results using the conservative approach, OW = 5 min

Summarizing, it can be drawn the following conclusions:

1. Increasing the parameter *n* implies reducing the number of requests for the dynamic connections.
2. The higher is the parameter *n* the lower is the experimented PLR.
3. The mean HT and IAT for the SC are compatible with the time required by the CP to establish/tear down a connection.
4. The higher is the parameter *n* the higher is the time percentage in which the SC is used to carry the HP traffic.

On the basis of such simulation results, we suggest to use the TRIDENT procedure implementing the conservative approach since it allows to cope with the PLR requirements of real-time client applications.

To further reduce the PLR, the THhigh can be decreased. As an example, for example, of using an OW of 5 minutes and THhigh = 90% of the interface capacity and *n* = 3, the experimented PLR is 1.10 E-03 which is lower than the case reported in Table 8 (1.92 E-03).