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TRIDENT: An automated approach to traffic engineering in IP/MPLS over ASON/GMPLS networks

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Abstract

This paper addresses the problem of designing a capacity management/traffic engineering procedure for an IP/MPLS over ASON/GMPLS scenario. We suggest TRIDENT, a procedure whose main goal is to dynamically provide the bandwidth required to transport through an ASON the MPLS–LSPs already established at the IP/MPLS client network. TRIDENT relies on automatically triggering demands to set up or tear down the ASON switched connections, and it is based on monitoring and predicting the offered traffic at the interfaces between the IP (MPLS) and the ASON layers. TRIDENT allows providing automatic Bandwidth on Demand (BoD) and it counteracts potential congestion at the client network. Its merits are evaluated by simulation results and it has also been experimentally tested.

Keywords: Traffic engineering; GMPLS; Traffic monitoring and prediction; Automatic bandwidth adaptation

1. Introduction

Time Division Multiplexing (TDM) legacy transport networks (e.g., SONET/SDH) have been basically designed for voice and leased line services. 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. The Information Age is consecrating the Internet Protocol (IP) as the integrating layer of most applications. Indeed, emerging applications, e.g., high-bandwidth multi-media applications (both real-time and no-real-time), shared access to remote resources, network-wide computation and data services (grid-computing, storage networking, etc.)

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are fuelling the increase of IP data-traffic, which typically is asynchronous, bursty and asymmetric [1].

As a consequence, the public network infrastructures have to cope with this increasing bandwidth demand and, at the same time, have to be able to support several classes of traffic with different requirements [2]. Although the introduction of Dense Wavelength Division Multiplexing (DWDM) systems is already providing high capacity links, more advanced network functionalities have to be introduced to face this problem in efficient and cost-effective way.

The simple bandwidth over-provisioning, which consists of dimensioning the network based on the peaks/surges of the traffic and which is the traditional approach used by the Network Operators (NO) for network planning, does not represent a cost-effective solution when NO want to reduce the infrastructure Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) [3].

Alternatively, the data traffic peaks can be handled by provisioning the bandwidth through the Network Management System (NMS), using a bandwidth scheduled approach [4]. However, to efficiently allocate bandwidth for transporting IP traffic, besides the traffic pattern, it is required to estimate the volume of the traffic peaks, which is not easy to do. In fact, the statistical characteristics of the IP data traffic are different from those of traditional voice traffic. IP traffic is highly dynamic; it is not as easily predictable and stable as the voice traffic, and it shows unpredictable peaks caused by unexpected events such as users' behavior, weather conditions, accidents, faults, etc. This causes significant and unexpected fluctuations over time (e.g., on daily-basis) of the aggregated data traffic to be transported by the telecommunication networks. Therefore, the bandwidth scheduled approach is not efficient.

The current transport networks (both SONET/SDH and Optical Transport Networks) tend to be static, which means that SONET/SDH circuits and light paths are provided "manually" through the NMS. This way of bandwidth provisioning is rather time consuming, which means that weeks or even months are needed to provide high bandwidth connections [5]. Thus, the introduction of intelligence in the transport networks (i.e., the ability to dynamically set up/tear down connections), is considered a promising solution to meet the above mentioned emerging requirements. A way to introduce intelligence is by the implementation of a distributed Control Plane (CP), which consists of a set of functionalities such as signaling and routing distributed throughout the network. The standardization of the Automatically Switched Optical Network (ASON) is recognized as the enabling solution to meet the requirement for fast and flexible end-to-end bandwidth provisioning [6], and the Generalized Multi-Protocol Label Switching (GMPLS) paradigm is proposed to be the control plane for the ASON networks. GMPLS is an extension of the set of protocols designed for the MPLS technology and it encompasses time-division (e.g., SONET/SDH, PDH, G.709), wavelength, and spatial switching [7]. ASON networks support leased lines service/permanent connections plus other two innovative transport services, namely, the soft permanent and the switched connections. Soft permanent connections are requested by the management plane, which uses network generated signaling and routing protocols via the Network Node Interface (NNI) to establish the connections, while the switched connections are requested directly by the client network via User Network Interface (UNI) signaling. The connections are then set up using NNI signaling and routing protocols [8]. The principles of automatic switching are applicable to both SDH transport networks and optical transport networks. In this paper, we focus on the switched connections service on optical networks.

We present a dynamic capacity management procedure (called TRIDENT) capable of cope with traffic fluctuations taking advantages of the automatic switching capabilities of ASON and the different priorities of the IP traffic. TRIDENT dynamically provides the bandwidth required to transport the MPLS-Label Switched Paths established at the client network through an ASON. Traffic Engineering (TE) rules are also defined in order to increase the utilization of the network resources.

The remainder of the paper is as follows: in Section 2 the capacity management problem is discussed while in Section 3 the suggested procedure is described. Section 4 presents some simulation results showing the effectiveness of the procedure and Section 5 presents its experimental implementation. Finally, Section 6 concludes the paper.

2. Capacity management for network resources optimization: related work

The provisioning of the connections/light paths required 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 an optical network. In the literature, two approaches have been considered for the virtual topology design, namely the off-line and the on-line approaches; while the former aims at the optimization of the virtual network topology according to a known traffic demand, the latter is applied when the traffic demand is not known a priori.

Concerning the off-line approach, many studies (such as [9–12]) present different procedures/algorithms designed for static wavelength routed networks.

Since a virtual topology optimized for a given traffic profile is not able to efficiently manage with dynamic traffic variations, different reconfiguration procedures in static wavelength routed networks to cope with these situations have been proposed in [13,14]. In both papers, the reconfiguration of the virtual topology is carried out in two steps, namely a first step to encompass the design of the virtual topology for the new traffic demands and a second step to make the transition from the old topology to the new one. However, the dynamics of the traffic demand are assumed to be known. For the on-line virtual topology 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 how to manage the reconfiguration itself (i.e., the proper set up/tear down of connections once the request is triggered by the client network). In particular, [1,15–17] focus on the second step.

The work described in [1] presents on-line algorithms/mechanisms to be used by ISPs to reconfigure MPLS networks while [15–17] propose algorithms for the on-line reconfiguration of IP/MPLS over ASON networks in order to optimize the network resources responding efficiently to dynamic traffic demands.

On one hand, [1] 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. In fact, 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, preemption mechanisms, and traffic rerouting in order to concurrently accommodate the largest amount of traffic and fulfill QoS requirements. More specifically, the TE system invokes an offline procedure to achieve global optimization of path calculation, according to an expected traffic matrix, while invoking an online routing procedure to dynamically accommodate, sequentially, the actual traffic requests (LSPs establishment requests).

In [15], the author defines a centralized integrated traffic engineering method based on the traffic routing stability. It reacts to new high priority and low priority MPLS LSP requests (characterized by a fixed bandwidth requirement of 10 Mbps) 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. LSPs requests are assumed to be triggered from the MPLS layer and thus triggering of the requests for light paths set up/tear down is not investigated. This work just deals with the efficient establishment of the LSPs over the optical networks and it does not take into account the fluctuations over time of the traffic carried by the LSPs already established. In fact, the reconfiguration is not based on the monitoring of the incoming traffic.

In [16], the authors define an on-line virtual topology adaptation procedure based on the actual traffic load, in MPLS over GMPLS networks. 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 optimize the accommodation of the bandwidth requests minimizing the costs involving bandwidth, switching and signaling. Also in this case, the triggering of the requests from the client layer is not investigated since it focuses on the efficient establishment of the LSPs over ASON/GMPLS networks.

Finally, [17] introduces and discusses how multilayer traffic engineering (MTE) in IP over ASON networks can be useful to manage the congestion experimented at IP layer through the automatic set up and tear down of switched connections. This paper basically discusses how to manage the reconfiguration of the network virtual topology. How to actually and efficiently monitor traffic loads in the network to trigger light path requests is not investigated. No TE algorithms to optimize the utilization of the network resources are investigated.

In this paper, we present a procedure which focuses on the above mentioned first step of the on-line virtual topology reconfiguration. It deals with the dynamic control of the available light paths at the optical transport layer to be used in IP/MPLS over ASON/GMPLS networks, and it is based on monitoring and predicting the offered traffic at the interfaces between the client and the ASON layers.

We assume that the establishment of the light paths is in charge of the distributed GMPLS-based control plane and, thus, it is out of the scope of this paper.

The closest approach to our work we found in the literature is done in [18]. This proposes a centralized approach to be used by the ISPs for the virtual-topology reconfiguration of a static WDM wide-area mesh network under dynamic traffic demand. The key idea of the procedure is to adapt the network virtual topology by periodically measuring the actual traffic load in the light paths, and reacting by either adding or deleting one light path at a time, in order to maintain the traffic load on each light path balanced between two watermarks.

Note that this procedure refers to static management plane-based optical networks. In fact, a centralized Network Manager, on the basis of the monitoring of the traffic on each light path, decides to trigger the reconfiguration of the entire virtual topology of the network. Once the reconfiguration is carried out, the Central Manager runs again the routing algorithms to accommodate all the actual traffic flows over the new virtual topology. Therefore, the network reconfiguration is thus not *automatic*. On the contrary, TRIDENT relies on the interworking between the client and the transport layer, which allows the detection of incoming traffic surges and *automatically* trigger the proper actions to cope with such traffic surges. TRIDENT introduces, apart from the monitoring step, a prediction step and it defines different priorities both at the client and at the optical layer.

3. TRIDENT: a procedure for dynamic capacity management in IP/MPLS over ASON/GMPLS networks

In this section we present TRIDENT (TRIggering DEmands mechanism for the connection set up and tear down in optical transport NeTworks based on traffic monitoring and prediction) a procedure supported by a patent [19], which is able to cope with the fluctuations of the aggregated data traffic to be transported by ASON/GMPLS networks. TRIDENT is an interworking procedure between the client network (IP/MPLS) and the circuit switched server layer of an ASON/GMPLS network supporting permanent and switched connections service for the dynamic use of transmission resources. It is based on monitoring and predicting the traffic crossing the routers interfaces. The aim of TRIDENT is to provide to NO, who own the transport networks, a procedure to efficiently transport the aggregated IP/MPLS traffic optimizing the transport network resources (keeping limited the size of the network) while providing Bandwidth on Demand (BoD) services.

Fig. 1 shows a potential scenario (IP/MPLS over ASON/GMPLS) where to apply TRIDENT.

This scenario consists of a multi-service network, which transport two traffic priorities, namely high and low priority traffic (HP and LP, respectively). The client traffic is classified as HP and LP Label Switched Paths (LSPs) according to the carried applications and/or according to the established Service Level Agreements (SLA). HP LSPs are bun-

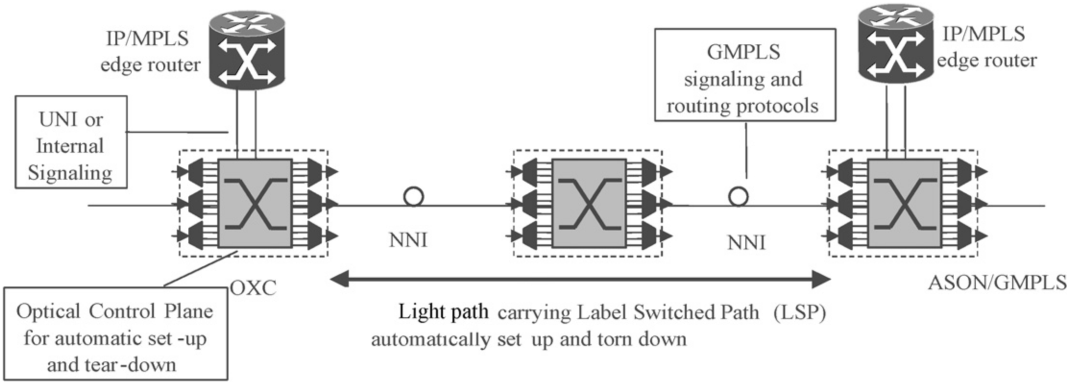


Fig. 1. IP/MPLS over ASON/GMPLS network scenario.

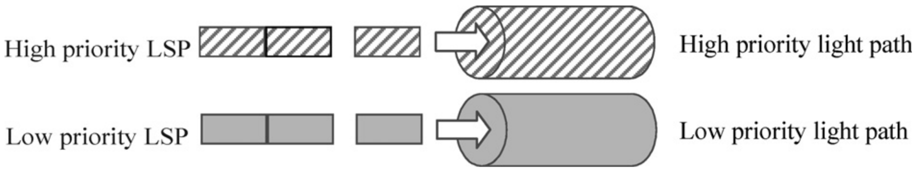


Fig. 2. Label switched paths are carried by light paths of the same priority.

dled onto HP light paths and LP LPSs are bundled onto LP light paths (Fig. 2). This allows the two types of light paths to 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.

In line with this scenario, we assume that some interfaces of the network nodes (layers 2 and 3) are directly allocated to the high priority traffic (supporting for example a number of permanent and switched light paths) and the rest of the interfaces are allocated to low priority traffic (supporting for example a number of switched light paths).

In such a scenario, TRIDENT runs in the three following steps:

1. *Monitoring and predicting the incoming traffic at client layer*. At this step the short-term prediction of the traffic crossing the router interfaces is carried out.
2. *Congestion management and optimization of the resources utilization*. At this step TRIDENT, based on the information provided by the first step, detects an over-load, regular or under-load condition on the HP light paths. In the case of an over-load condition (potential congestion at the client layer), a request for the set up a switched optical connections is triggered. Once the surge has passed, when an under-load condition is detected, the initial condition is restored through the tear down of the previously established switched optical connection. This way the size of the network is kept limited.
3. *Automatic set up/tear down of switched optical connections*. At this step, the connection requests triggered by the second step are handled. The GMPLS-based control plane set up/tear down the switched connections required.

Fig. 3 depicts the interactions among the three steps which are described in detail in Sections 3.1–3.3.

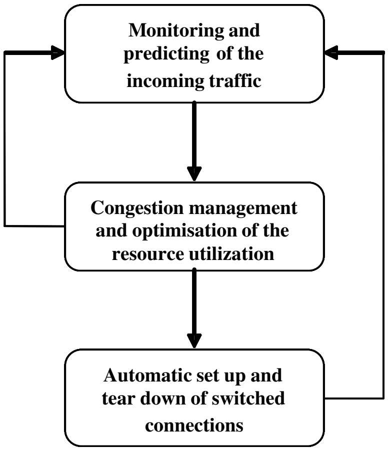


Fig. 3. The three steps of the TRIDENT procedure.

3.1. *Monitoring and predicting 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 [20]. We used periodic monitoring of the incoming traffic in order to automatically adapt the network resources at the transport layer to the current network conditions in real time. To enforce the traffic monitoring and to minimize the traffic losses at the client layer in case of traffic peaks, we also introduce a short-term prediction algorithm, which is one of the novel aspects of TRIDENT. The implementation of a prediction algorithm advantageously allows detecting in advance the occurrence of a traffic surge, so that the network controller may have time to take the suitable decision in order to cope with the surge.

For the traffic monitoring, the Simple Network Management Protocol (SNMP) is used. SNMP is characterized by a simple set of operations that allows the devices to be remotely managed and controlled [21].

Traffic monitoring can be performed on: Flow-basis, interface-basis, link-basis and node-basis. TRIDENT is based on monitoring and predicting the traffic crossing the routers interfaces as well as the actual traffic of the MPLS LSPs. We have investigated if current commercial IP/MPLS routers support the monitoring of the actual traffic carried by the LSPs. We have found that commercial MPLS routers are able to support MPLS-based traffic measurements [22,23].

In the TRIDENT procedure, the collection of the data traffic samples is carried out periodically 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 router interface (hereafter B), the adaptive Normalized Least Mean Square (NLMS) error linear predictor [24,25] was used. We used a linear algorithm in order to avoid increasing excessively the complexity of this step. Since it is an adaptive approach, we used it as an on-line algorithm for forecasting the aggregated traffic bandwidth requirements. Generally speaking, a k-step linear predictor is concerned with the prediction of the next kth sample of the signal $x(n)$, which means that by 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 $l = 0, 1, \ldots, p-1$ 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.

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. 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 $\mu = 0.01$.

Focusing on the TRIDENT procedure, $X(n)$ represents the traffic crossing the router interfaces and we defined the following variables:

- Prediction sample period $= \tau$.
- Number of prediction sample periods used to predict the kth future value of $x(n): p$.

At time t_0, the past p samples are used to predict the traffic value for at the time $(t_0 + k * \tau)$.

3.2. Congestion management and optimization of the resource utilization

As mentioned above, the objective of this step is to detect, at the end of each OW, the potential occurrence of an over-load condition on the HP light paths. When an over-load condition is detected, at this step it is decided whether or not automatically trigger the request to set up an additional switched light path to absorb the peaks causing the over-load condition. Once the peak has passed (an under-load condition is detected) the initial condition is restored, that is, the request for the tear down of the additional switched connection is triggered. TRIDENT relies on the threshold-based policy depicted in Fig. 4. The predicted traffic crossing the HP interface n (i.e., B_n) obtained from the step 1, is compared with the thresholds of over-load ($\mathrm{TH}_{\mathrm{high}}$) (hereafter high threshold and low threshold, respectively). Then, a decision making function automatically manages the way to admit the high priority data traffic to proper connections.

When the over-load condition is detected on a light path supported by the interface n, firstly, a tentative to reroute some HP LSPs from this light path to other already established HP light paths towards the same destination node is done. If it fails, this step 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 temporarily available for the high priority traffic. Then, the request for the set up of an additional HP light path is triggered to the node control plane. Once the peak has passed and an under-load condition is thus detected on the light path supported by interface n, the request for the tear down of the additional light path is triggered. In this way TRIDENT allows to keep limited the size of the network. It has to be highlighted that we assume that the initial network topology is properly designed since TRIDENT does not manage the tear down of light paths with an

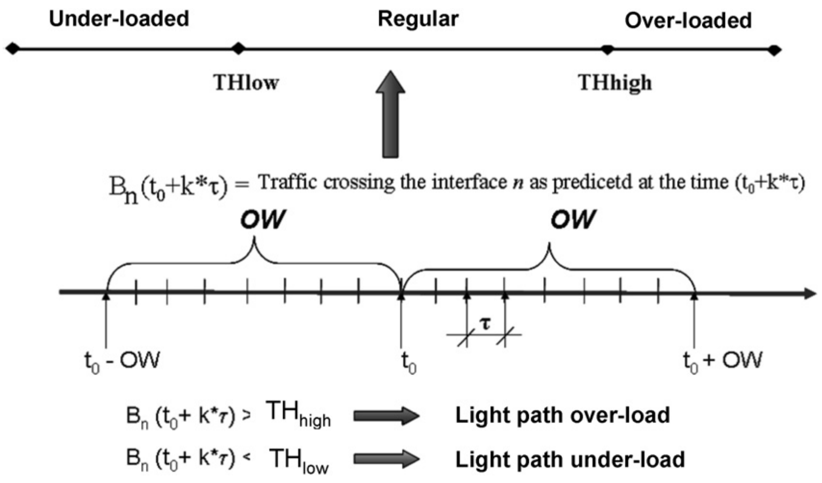


Fig. 4. Threshold-based policy for congestion management and resource utilization optimization.

under-utilization condition. The details of the set up/tear down triggering algorithms are reported in Sections 3.4 and 3.5.

The election of the thresholds value is the result of the compromise among different parameters, namely: (1) The stability of the higher network layers, (2) The routing and signaling cost functions since it has to be avoided to set up/tear down optical connections too often, (3) The packets lost at the high priority router interfaces, which are equipped with limited buffers, due to the sudden increases of the HP traffic (hereafter Packet Loss Rate, PLR), and (4) The bandwidth utilization of the light paths.

3.3. Automatic set up/tear down of the switched connections

If the previous step triggers the request for set up/tear down of additional switched connections to absorb the HP traffic peaks, it is done by the Control Plane (CP) through the Network-Node Interface (NNI) routing and signaling [6,26]. Fig. 5(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.

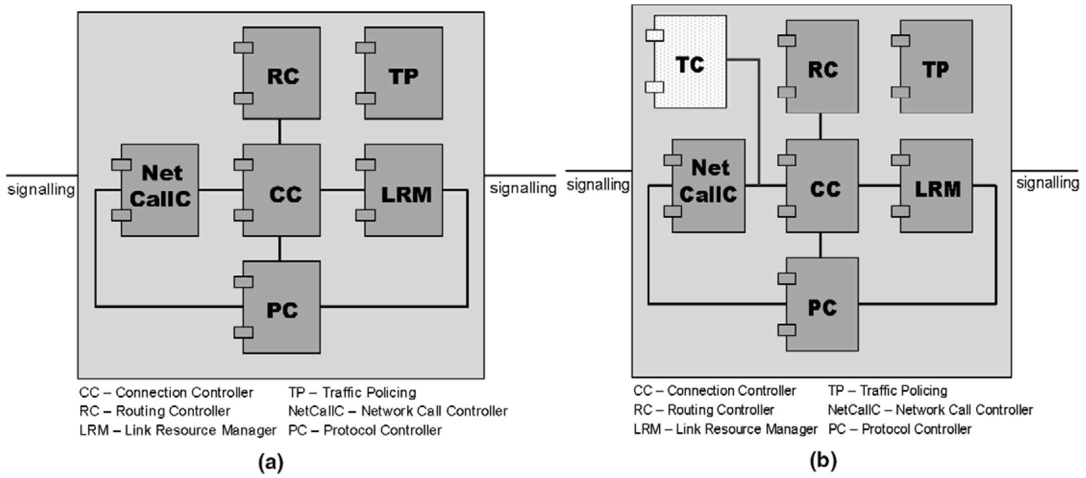


Fig. 5. Optical control plane: (a) ITU-T architecture and (b) TRIDENT procedure: adding the traffic control component.

TRIDENT requires a slight modification of the control plane architecture defined by the ITU-T [6] (Fig. 5(a)). In fact, it requires the introduction of a Traffic Control (TC) component (Fig. 5(b)). It is responsible for the collection of the raw data on the router interfaces, elaborating these data to predict the traffic trend and then making a decision whether or not requesting (e.g., via UNI or internal signaling) to the Optical Connection Controller (OCC) of the Control Plane, the set up/tear down of a switched connection.

3.4. Illustrative example of how TRIDENT works

Fig. 6(a) and (b) depict an example of how the procedure works. Let us suppose that 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 supported by the router interface n (i.e., $B_n > \mathrm{TH}_{\mathrm{high}}$), first a tentative to reroute some HP LSPs (starting from the least loaded one) is done. If it fails, a request for the set up of an additional HP light path is triggered to the node control plane to be used temporarily to absorb the HP traffic peak. Then, some network resources are requested to the server layer to be torn down in order to make them temporarily available for the HP traffic. The node interface made available at the server layer is used for setting up the HP switched light path to accommodate the traffic peak, thus avoiding the network congestion (Fig. 6(b)).

Once the requested switched connection is established by the distributed GMPLS-based control plane (supported for example by the router interface t), the predicted high priority traffic is then accommodated (starting from the most loaded LSP) into the new light path. Once the traffic surge on the permanent connection expires (i.e., $B_n < \mathrm{TH}_{\mathrm{low}}$), the HP switched light path previously allocated (using the router interface t) is torn down (after the allocation of the LSPs onto the HP light path supported by the interface n) and the network resources are restored to the initial conditions (the interface t can be used again to establish LP light path to transport LP traffic).

3.5. TRIDENT procedure: algorithms description

Fig. 7 shows the pseudo-code for TRIDENT to handle an HP traffic peak on the HP interface n.

When the traffic surge expires the switched HP connection previously allocated is torn down and the network resources are restored to the initial conditions. Fig. 8 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 peak.

4. Performance evaluation

Extensive simulations were carried out to evaluate the performance as well as the effectiveness of TRIDENT to handle high priority traffic fluctuations. The simulated network consisted of IP/MPLS edge routers connected through a meshed-based topology ASON/GMPLS network.

Two case studies were considered, namely one aiming at obtaining the number of high priority light paths required to carry a certain high priority traffic load, and the other aiming at illustrating the effectiveness of the procedure in case of unexpected traffic surges. In the first case study, we mainly focused on the influence of the different parameters of the procedure on its performance.

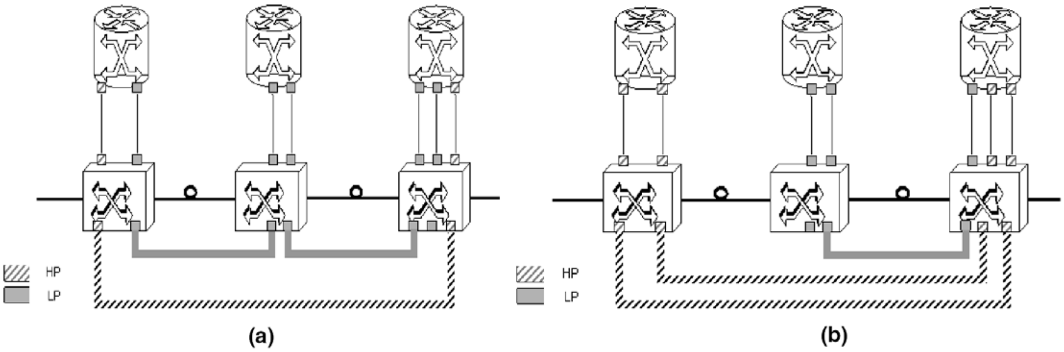


Fig. 6. TRIDENT procedure: (a) initial conditions and (b) conditions after tracking the HP traffic peak.

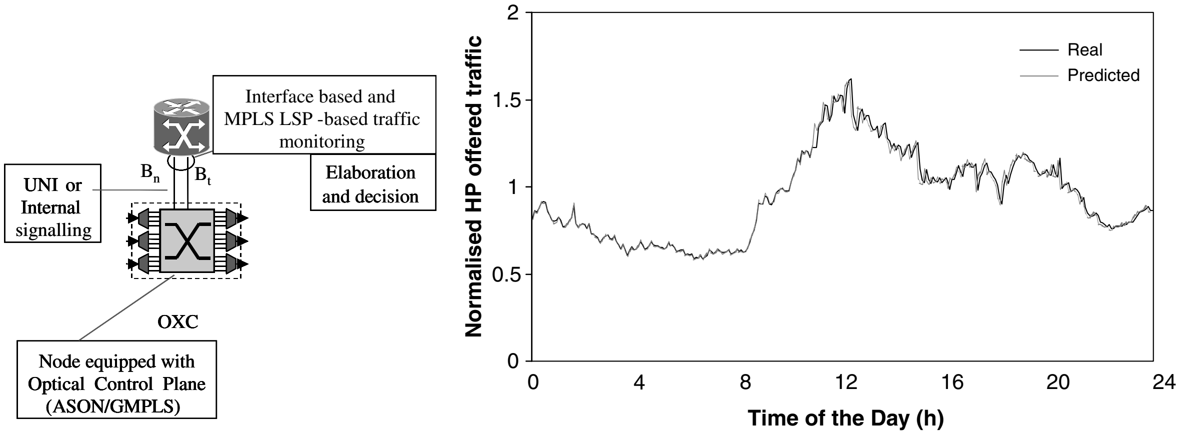
```
Input: Monitoring of the traffic crossing the interface $n$, $B_n$

Output: 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 same destination node on router interface $t$ exists)
            while (($B_t$ < High Threshold)&($B_n$ > High Threshold))
                1. Tag of the least loaded LSP to be rerouted for load balancing
                2. Update $B_t$ and $B_n$
        endif

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

            1. Request for the tear down of LP light path on the router interface $t$
            2. Triggering of the request for the set up of a HP light path on the router interface $t$, tagged as HP

                if (HP light path supported by interface $t$ is established)
                    While ($B_n$ > High Threshold)
                        Reroute of the most loaded LSP for load balancing on light path supported by $t$
                        Update $B_n$
                    endwhile
                else
                    Reroute of the tagged LSPs
```

Fig. 7. TRIDENT procedure, handling HP traffic peak 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 most loaded LSP 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 LSPs
            2. Request for the tear down of the HP light path supported by router interface $t$
            3. Request for the set up of LP light path on router interface $t$

    endif
```

Fig. 8. TRIDENT procedure, handling the end of the HP traffic peak on HP interface *n*.

Specifically, we evaluated the influence of the high and the low threshold values, as well as of the size of the Observation Window (OW). In the second case study, we showed how TRIDENT allows to



(a) (b)

Fig. 9. (a) Source node at which the procedure is applied and (b) daily HP IP/MPLS traffic profile between the source and the destination nodes.

promptly react to the unexpected fluctuations of the client traffic, diverting LP network resources to cope with the HP surges.

Fig. 9(a) shows the source node at which TRIDENT is applied. It consists of an IP/MPLS router which is composed by an "access" router collecting all the incoming traffic from different client networks (i.e., ISPs) and an OXC equipped with a GMPLS-based control plane.

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, Fig. 9(b) shows the daily HP traffic profile (normalized to the router interfaces capacity and averaged over 5 min) between the two nodes.[1] By applying the TRIDENT procedure, the traffic crossing the router interfaces is monitored and predicted periodically during the OWs. At the end of every OW, a connection set up or tear down request is triggered if required according to the algorithms described in Figs. 7 and 8. In particular, for the prediction algorithm the parameters were set up to the following values: $p = 12$, $k = 3$ and $\tau = \mathrm{OW}/3$. Fig. 9(b) also depicts the predicted traffic resulting form the application of the NLMS algorithm (described in Section 3.1).

Let us suppose that initially one router interface, (tagged as HP and 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.

Fig. 10 depicts the number of established HP light paths versus the time, which are used to transport the HP traffic (that of Fig. 9(b)) between the source and observed sink node. For this simulation, we set the high threshold ($\mathrm{TH}_{\mathrm{high}}$) to 95% of the interface capacity while the low threshold ($\mathrm{TH}_{\mathrm{low}}$) was set to 40% (Fig. 10(a)) and 60% (Fig. 10(b)), respectively. Observation Windows of 1 min 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.

Note that, 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 (about the 50% of the time); otherwise it can be used, for example, to provide new potential services (e.g., dynamic connections for Storage services) connecting the edge router towards other destination nodes. This means that, by applying TRIDENT, there is some additional capacity available in the network with the same number of network resources.

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[1] The daily traffic profile corresponds to a real traffic trace captured from the Catalan Academic Network (Anilla Cientifica) in September, 2003.

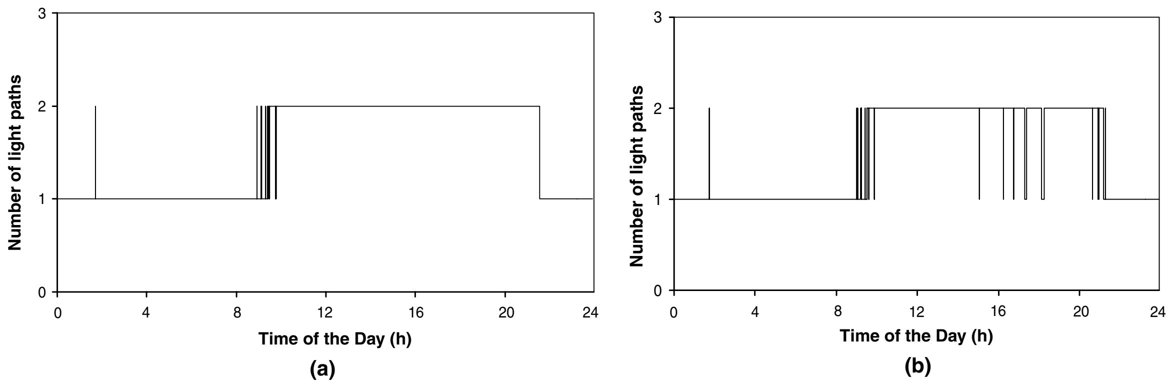


Fig. 10. Number of light paths needed to carry the high priority IP/MPLS traffic: (a) $TH_{low} = 40\%$ of the interface capacity, (b) $TH_{low} = 60\%$ of the interface capacity.

Concerning the evaluation of the impact on the performance of TRIDENT 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 excessively increasing the cost of the routing and the signaling functions of the GMPLS-based control plane.

We firstly evaluated the influence of the high threshold (TH_{high}) when maintaining fixed the low threshold (TH_{low}). It influences both the bandwidth utilization of the permanent connection and the PLR. Specifically, as depicted in Table 1, the higher the high threshold is, the higher is the bandwidth utilization. This is because, when the high threshold is increased, the over-load condition, and consequent request for the HP switched connection, is detected when the actual bandwidth utilization of the permanent connection is higher. However, increasing TH_{high} implies that there are more packets lost at the router interfaces as a consequence of the sudden increases of the HP traffic. In fact, as shown in Table 1, the experimented PLR is higher.

On the other hand, Table 1 and Fig. 10 show the effect of the increase of the low threshold (TH_{low}) value. Specifically, Fig. 10 shows that 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 the lower is the mean holding time obtained for the switched connection.

TH_{low} 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 to tear down of a switched connection previously set up), 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 1). 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 signaling cost functions. Besides, the higher the low threshold is the higher is the PLR (see also Table 1). As a solution to avoid requesting set up/tear down switched connection too often, we define a conservative approach. It

Table 1
Impact of the TH_{high} and TH_{low} thresholds

$TH_{high} = 95\%$ $TH_{low}(\%)$	Mean bandwidth utilization (%)	PLR	$TH_{low} = 60\%$ TH_{high} (%)	Mean bandwidth utilization (%)	PLR
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

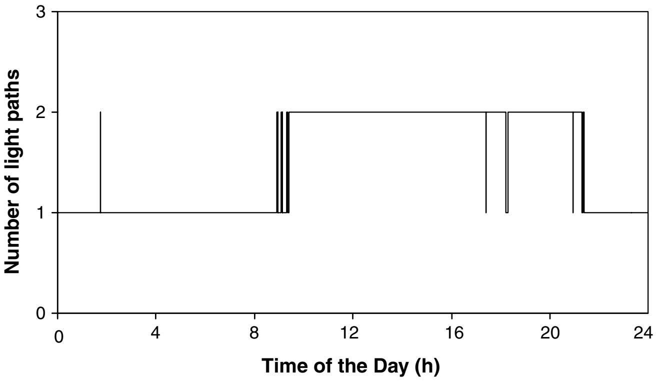
consists of holding the switched connection even if it is not strictly required, which means that the request for the tear down of the HP switched connection is triggered only when the experimented under-load condition is repeated again for a certain number of consecutive (tear-down counter, s) OWs. As an example, Fig. 11 shows the light paths established to carry the client traffic by applying the conservative approach with $s = 3$. This result corresponds 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. Note that in this case, the mean number of requested light paths is lower than when the conservative approach is not used. Also, in this case, the PLR is lower. The price to pay for this is that the bandwidth utilization of the permanent connection decreases (see Fig. 11(b)).

Of course, the conservative approach can be implemented also at the set up stage but in this case, it would imply higher figures for the PLR.

An alternative to reduce the number of requests for the set up/tear down of the switched connection is based on increasing the size of the OWs. As an example, Fig. 12(a) and (b) show the number of the light paths established to carry the HP traffic when OWs of 3 and 5 min 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 min).

Obviously, when increasing the OW size, the experimented PLR increase (see Table 2).

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

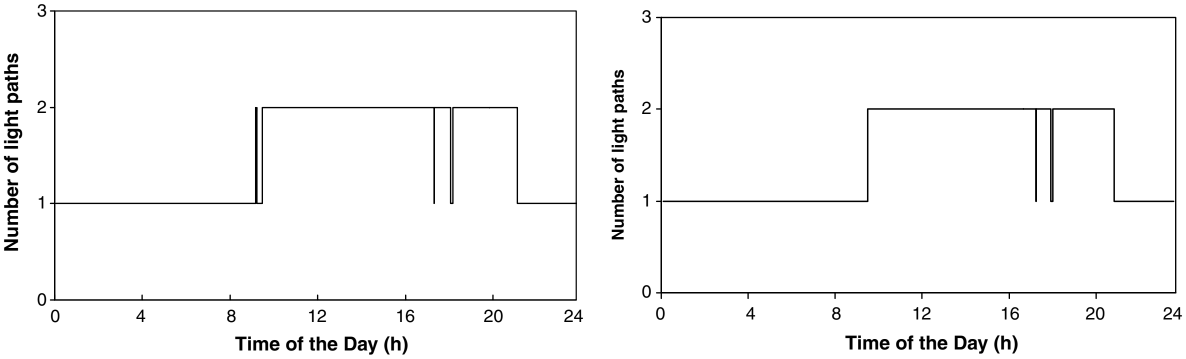


(a)

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

(b)

Fig. 11. (a) Number of light paths using the conservative approach and (b) average bandwidth utilization of the permanent connection and experimented PLR.



(a) (b)

Fig. 12. Number of light paths increasing the OW: (a) OW = 3 min and (b) OW = 5 min.

Table 2
PLR when increasing the OW

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

Table 3
Improving PLR by using the prediction step

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

traffic prediction provides better PLR figures than the cases without prediction. As an example, he Table 3 shows the comparison when using OW of 3 and 5 min, respectively, and setting the TH_{high} and TH_{low} to 95% and 60% of the interface capacity respectively.

Finally, it can be observed that the thresholds value can be dynamically changed on the basis of the actual bandwidth utilization of the light paths and/or on the basis of the actual PLR. For example, we can introduce an 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 utilization and PLR during the previous UW.

The results of the second case study aim at evaluating the effectiveness of the procedure in case of having unexpected traffic surges. The HP traffic profile showed in Fig. 13(a) is the daily traffic profile between the two observed nodes. If compared with the traffic profile of Fig. 9(b), it is characterized by an unexpected traffic surge which appears at noon. In this case the procedure, contrarily to both the over-provisioning and the scheduled approach, is able to promptly react to the incoming traffic surge adapting the bandwidth to the traffic. Fig. 13(b) was obtained with the high threshold set to 95% and the low threshold set to 60% of the router interface capacity, an OW of 5 min long and using the conservative approach with $s = 3$.

Finally, Table 4 summarizes the results obtained when OW 1 min long was considered. It refers to the number of set up/tear down requests, the percentage of time the additional HP light path is required and the mean Holding Time (HT) and IAT (InterArrival Time) for the switched connection were obtained. It shows that the percentage of time (calculated over the simulation time, i.e., 24 h) the HP switched connection is required, is about the 50%. 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.

On the basis of such simulation results, we suggest to use the TRIDENT procedure implementing the conservative approach since it allows coping with the PLR requirements imposed by the real-time client applications. To further reduce the PLR, the TH_{high} can be decreased.

5. Experimental results

In order to verify the feasibility of the TRIDENT procedure in an experimental environment and to complement the simulation results, we also carried

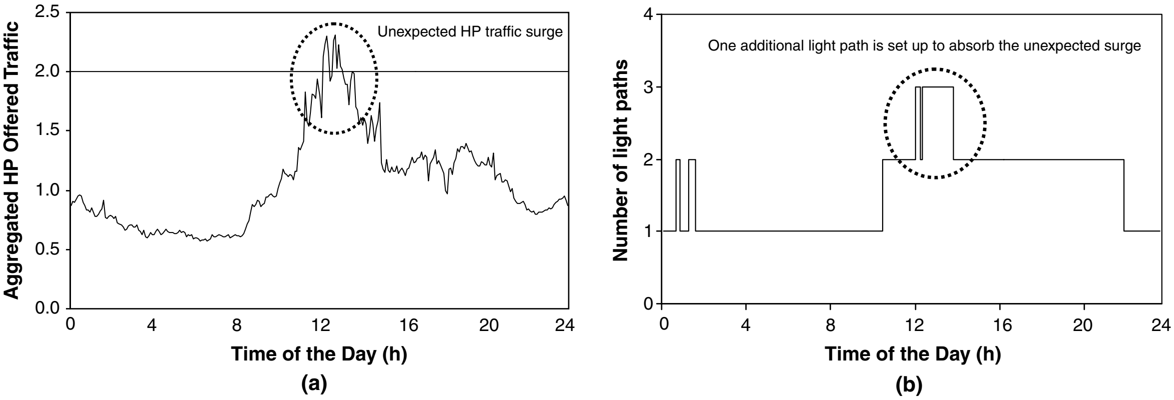


Fig. 13. (a) HP client traffic with unexpected burst/surge, (b) number of HP light paths required.

Table 4
OW = 1 min, summary of simulation results

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

[a] Calculated over the simulated time.

out its implementation in a GMPLS-based IP/SDH testbed available at the Telecom Italia Lab (TILAB) premises [27].

The testbed is composed by 6 Fiber Switch Capable (FSC) Optical Cross Connects (OXCs) and IP routers 12000 series from Cisco Systems (Fig. 14). The Data Communication Network (DCN) which interconnects the Optical Connection Controller (OCC) of the different nodes, is based on Fast Ethernet technology while the transport plane consists of a FSC-based ASON network.

According to the GMPLS hierarchy [7], the FSC-capability means that the OXCs switch from one incoming fiber to outgoing fibers. This switching capability is due to the utilization of optical switching matrixes based on Micro Electro Mechanical Systems (MEMS) technology [28].

The experimental implementation was based on a simplified version of the TRIDENT procedure, since the MPLS layer was not available. In the testbed, only the high priority traffic is considered, and spare SDH-based Synchronous Transport Module (STM)-1 interfaces instead of low priority interfaces were used when the resources dedicated to the HP traffic are not sufficient.

As HP traffic generator, a Router Tester from Agilent Technologies was used. The generated HP traffic is in the order of hundreds of Mbit/s, to be compatible with the capacity of the STM-1 interfaces.

For traffic monitoring purposes, SNMP-based software was used in order to make a polling of the number of bytes that cross the router interfaces. Every 20 s, a request to the IP router is triggered for how many bytes have passed through a certain interface. After two time consecutive requests the traffic crossing the interface is calculated.

To make feasible the request for the automatic set up/tear down of connections, a Craft Terminal (CT) was developed. Basically the CT was in charge to open a socket to talk to the CP of a node interchanging strings, and this way, the CT allows the request to the CP the connection set up/tear down.

Initially some STM-1 interfaces were set up and additional STM-1 interface were used as spare inter-

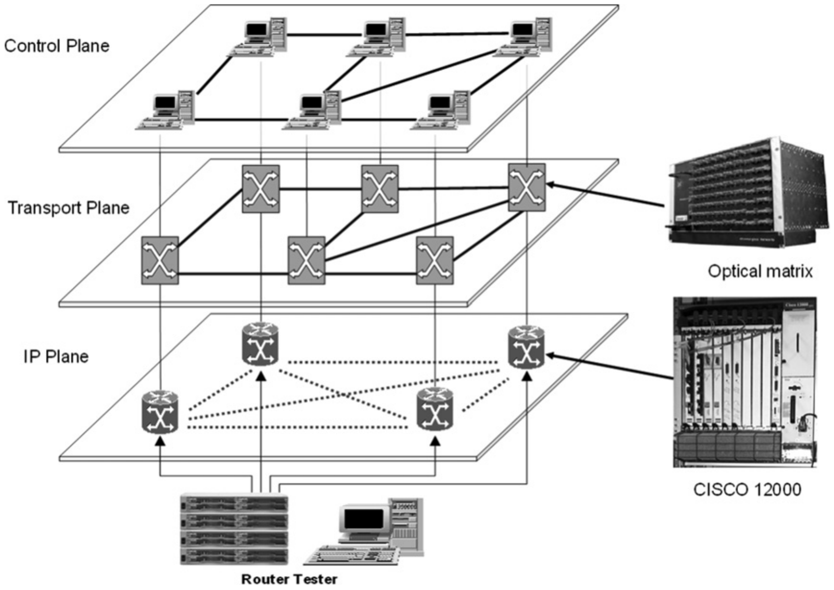


Fig. 14. TILAB testbed: transport and control plane.

faces when the procedure required to set up/tear down an additional interface to absorb the traffic surges. The PLR parameter was used as one of the metrics for the performance evaluation of the procedure.

As a sample of the results obtained in the experiments, Figs. 15 and 16 depict the number of STM-1 connections required to transport the exemplary of HP traffic generated by the router tester.

The generated traffic represents the HP traffic from one source node towards a destination node from 7 a.m. to 21 p.m. (about 14 h). The TH_{High} and the TH_{Low} were set to 99% and 96% of the capacity equivalent to two STM-1 interfaces (e.g., 296 Mbps).

Fig. 15 shows the result obtained for an OW of 5 min. The number of STM-1 connections used to carry the HP traffic rises and falls according to the traffic dynamics. The measured PLR was 3.8E−04.

To avoid requesting the set up/tear down of connections too often, we implemented the conservative approach discussed in Section 4. Fig. 16 reports the number of STM-1 connections when the conservative approach with $s = 2$ is applied and OW is set to 5 min. In this case, the measured PLR was equal to 2.42E−04.

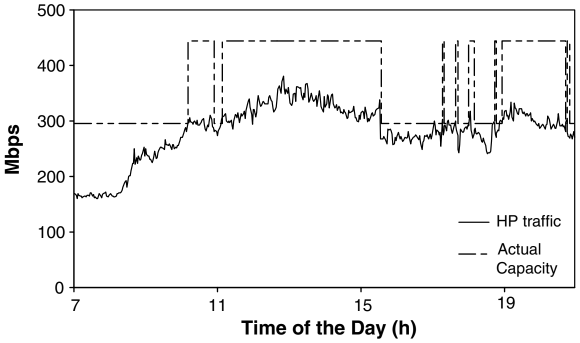


Fig. 15. Experimental result, number of STM-1 connection required.

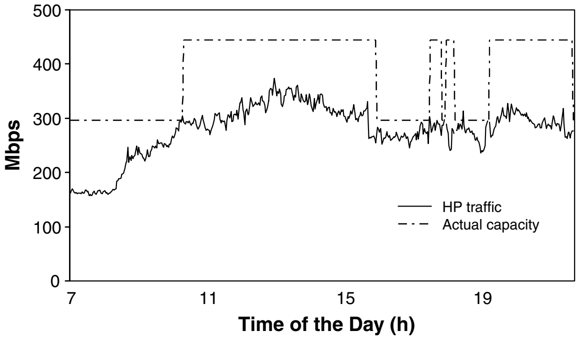


Fig. 16. Experimental result, number of STM-1 connection required with the conservative approach.

These experimental results show that the TRIDENT procedure can be applied to a real environment. Both the traffic monitoring and short-term prediction can be performed even with the current technology. The experimental results are in line with the simulation results since they show that the parameters of the procedure have the same influence on the performance of the procedure itself.

6. Conclusions

In this paper we have considered an IP/MPLS over ASON/GMPLS scenario where we have defined TRIDENT, a procedure for the dynamic management of the capacity available at the optical transport layer. By monitoring and predicting the traffic crossing the IP/MPLS routers interfaces, TRIDENT automatically triggers the request for the set up/tear down of switched connections to track with the client traffic fluctuations.

The simulation results show that, without requiring any knowledge of the incoming traffic pattern, TRIDENT promptly reacts to the dynamic traffic fluctuations providing the bandwidth required to transport the MPLS–LSPs already established at the client layer. TRIDENT allows efficiently managing both network over-load and under-load conditions.

Simulation results also show that by adequately configuring the TRIDENT parameters, it provides very good figures for the bandwidth utilization of the light paths, and that by applying the conservative approach, it minimizes the IP packet losses and it reduces the number of requests to the ASON control plane. By minimizing the IP packet losses, TRIDENT allows meeting the QoS requirements imposed by the real-time applications, and by reducing the number of connection demand requests, TRIDENT is able to efficiently track the client traffic fluctuations, without excessively increasing the cost of the routing and signaling functions.

On the other hand, the mean holding time and interarrival time obtained in the simulations for the switched connections are compatible with the time required by the control plane to establish/tear down them.

On the basis of these simulation results, the final conclusion is that TRIDENT performs better when applying the conservative approach.

Finally, we have implemented TRIDENT into a real GMPLS-based IP/SDH testbed, obtaining experimental results that demonstrate the feasibility of this procedure to be implemented in real networks.

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