7 Summary and Final Conclusions

The Information Age is consecrating IP as the integrating layer of most applications. This is fuelling the increase of data traffic, characterized by its typical asynchronous, burst and asymmetric nature.

On one hand, the introduction of ASON/GMPLS network solutions is, in a medium/large term the most interesting approach to meet network emerging requirements, not only to overcome the four fundamental network problems (bandwidth, latency, packet loss, jitter) for transporting traffic in real time, but also to enable flexible, automatic and fast provisioning of bandwidth, automatic discovery, multi-layer traffic engineering and multi-layer resilience.

On the other hand, for metropolitan environments, the emerging RPR packet-based technology seems to be, in a short term, the most promising technology to substitute the legacy SONET/SDH-based networks, which have been designed and optimised for voice-based applications. In contrast, RPR was specifically designed to transport data (IP) traffic.

This Thesis includes four contributions. The first one proposes the capacity management/traffic engineering TRIDENT procedure for the automatic set up and the tear down of switched optical connections based on the monitoring and prediction of the aggregated IP/MPLS packet traffic to be transported by an ASON/GMPLS network. Specifically the procedure deals with the dynamic establishment of optical connections in order to track the client traffic fluctuations.

Without requiring any knowledge of the future aggregated traffic pattern to be carried, the suggested procedure allows to provide, time-dynamically, the bandwidth required to transport through the ASON/GMPLS transport network the MPLS-LSPs already established at the IP client layer while avoiding network congestions and bandwidth connections under-utilisation.

Both the simulation and the experimental results show the feasibility of the procedure, which allows to promptly reacting to dynamic changes in the client traffic. The main requirements of the procedure are to maximise the utilisation of the bandwidth of the optical connections, to limit the number of connections set up requests to have HT and IAT statistics compatible with the CP requirements and finally to minimise the IP packet losses.

The extensive simulation results presented in this Ph. D. report show that by adequately configuring the procedure parameters, it provides high figures for the bandwidth utilization of the light paths reaching in such a way traffic engineering objectives. At the same time, by applying the conservative approach, TRIDENT allows to keep limited the IP packet losses as well as the number of request to the GMPLS-based control plane for connections establishment. The former implies that TRIDENT allows meeting the QoS requirements imposed on the transport network by real-time applications while the latter implies that it is able to track the client traffic fluctuations without excessively increase the cost of the routing and signalling functionalities.

Also we present the experimental results that show the feasibility of the procedure in a real network environment.

Summarising, the TRIDENT procedure offers two opportunities to the Network Operators, namely: 1) providing, automatically, Bandwidth on Demand services according to the dynamic bandwidth needs and 2) avoiding, in real-time, network congestions and allowing resource utilisation optimisation by applying Traffic Engineering rules. Furthermore it allows offering different classes of transport services since low priority traffic is transported only by low priority optical connections reserving thus high priority resources for the high priority traffic.

Thus, TRIDENT procedure really represents a cost-effective solution for Network Operators since it avoids the over-dimensioning of the network (enabling network CAPEX and OPEX reductions) while cope with both the requirements of the client network and of the GMPLS-based control plane.

The second contribution proposes a preliminary practical approach for ASON networks dimensioning purposes based on the approximate characterisation of the traffic arrivals process. The simulation results indicate that the classical teletraffic theory (in particular the classical Engset analytical model) seems to be suitable for ASON dimensioning while an exact model is not available. The proposed analysis framework, in spite of its limits, aims to be useful as a reference scheme in real business cases both for Network Operators and Vendors.

The optimisation of the network resources is very critical in case of failures. Since failures can occur at each layer composing the network, as the third contribution we propose a novel multi-layer resilience strategy based on the interworking between the RPR layer and the optical layer to be applied in an IP/RPR over OTN metropolitan network scenario. Specifically, we propose the Double Hold-Off Timer (DHOT) as a coordination strategy between the recovery mechanisms of RPR and those implemented at the optical layer. It is a novel approach which improves the performance of the already proposed hold-off timer coordination approach (SHOT), allowing to the network to better and faster cope with different failure scenarios.

A recovery strategy to be implemented in real network environments, need to be simple from the implementation point of view, feasible, and need to minimise the time of the interruption of the provisioned services, which means to minimise the losses arising from the failure occurrence.

The suggested DHOT approach is simple since it is based on timers, it is feasible since it is even compatible with the current status of RPR and optical technologies and it allows to react to network outages in a fast and effective way. Moreover, simulation results demonstrate that the DHOT, compared with the hold-off timer approach, works better in terms of recovery since lower recovery times and traffic losses are obtained in the case of failures in the higher network layers (for above the optical transport layer). In this case, the DHOT approach allows a traffic losses reduction, in certain conditions, of about the 70% with respect to the SHOT.

Nevertheless, the RPR protection mechanisms, although very efficient and fast, provoke the substantial reduction of the available bandwidth due to the required ring reconfiguration. In order to avoid the ring saturation, the traffic inserted in the ring by the higher layers has to be kept limited, which implies a very low bandwidth utilisation in a failureless state.

The fourth contribution of this Thesis propose the use of the automatic switching capability provided by the ASON/GMPLS networks to allow to keep the very high ring bandwidth utilisation provided by the RPR technology, even when the network reconfiguration is required (in case of failures). Specifically, we propose to implement in each IP/RPR router a monitoring function to monitor periodically the bandwidth utilisation of the light paths connecting the IP/RPR routers and by using a threshold-based policy, to use the switched services to cope with the ring saturation and under-utilization. This procedure allows to react to the traffic fluctuations and on the other hand it avoids to limit the traffic inserted in the RPR ring, improving the bandwidth utilisation.

8 Future Work

From the contribution provided by this Thesis many different lines of future work may arise.

Regarding the TRIDENT procedure, future investigations can deal with its signalling and routing aspects. As an example it will worth to investigate if current routing algorithms could be used in a network environment implying the frequent change of the network topology, above all in inter-domain environments.

Another line of future work regards the dimensioning of the ASON networks. The methodology suggested in this Thesis strongly depends from the procedure used to automatically adapt the available bandwidth at the optical transport layer on the basis of the fluctuations of the traffic of the client network. A further step implies to investigate the suggested methodology when the TRIDENT procedure is applied.

Regarding the RPR technology, when a new strategy is defined, it should interwork smoothly with existing protocols. For this reason, it will be future work the study of the interworking with the higher layers (for example the MPLS protocol) and with the underlying optical transport layer, not only related to the protection mechanism but also for the optimization of the network resources. As an example, the investigation of the applicability of the TRIDENT procedure to IP/RPR over ASON/GMPLS networks will be another point of future investigations.

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Appendix: List of publications

1. **S. Spadaro**, A. D'Alessandro, A. Manzalini, J. Solé-Pareta, "A procedure for automatically triggering the set up/tear down of switched connections in IP(MPLS) over ASON network", submitted to the Elsevier Computer Networks Journal.

2. **S. Spadaro**, A. D'Alessandro, A. Manzalini, J. Solé-Pareta, "A procedure for automatically triggering the set up/tear down of switched connections in IP(MPLS) over ASON network", Workshop on Recent Advances in Computer Networking, April 10, 2004, Atlanta, USA.

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1. IST-1999-11387 LION project "Multilayer resilient network planning and evaluation: preliminary results", Deliverable D10, January 2001

2. IST-1999-11387 LION, "Resilience Interworking strategies for Multi-layer Networks", Deliverable D16, October 2001

3. IST-1999-11387 LION, "Multilayer resilient network planning and evaluation: intermediate results", Deliverable D19, December 2001

4. IST-1999-11387 LION, "Optimisation of Network Architectures", Deliverable D18, December 2001.

5. IST-1999-11387 LION, "Multilayer resilient network planning and evaluation: final results", Deliverable D24, November 2002

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Other Publications

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