Circuit/Wavelength Switching and Routing

Report of the Achievements of the COST-action 266

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Abstract — **This paper gives an overview of the work carried out during the course of the COST-266 action on circuit/wavelength switched network studies. Several subjects are discussed in detail in this paper. A first important topic deals with the different control plane models in single- and multi-domain networks. A second important issue is the routing and wavelength assignment problem, both in networks with static and dynamic traffic demands. Also the IP-over-OTN network architecture, envisaged to be the network architecture most suited for future transport networks, is discussed. Finally the study on optical virtual private networks is presented.**

Keywords - circuit-switching, WDM networks, control plane, routing and wavelength assignment, IP-over-WDM, optical virtual private networks

I. Introduction

The COST-program is a European program for Co-Operation in the field of Scientific and Technical Research in Telecommunications. For the last four years, the COST-action 266 on "Advanced Infrastructure for Photonic Networks" [1] has extensively studied aspects related to optical networking. These studies covered the whole range from the physical level (e.g. transmission effects like dispersion, etc.) up to the network level and the service level. The study of the optical network was not limited to circuit/wavelength switched networks, but included also an investigation of networks based on optical burst switching and optical packet switching. Special attention was also given to the reliability aspect.

7th International Conference on Telecommunications - ConTEL 2003
ISBN: 953-184-052-0, June 11-13, 2003, Zagreb, Croatia

This paper reports on some of the major achievements of the project with respect to circuit/wavelength switched networks. In such networks, network nodes are interconnected by optical fibers. Per fiber, several wavelength channels are multiplexed making use of the Wavelength Division Multiplexing (WDM) technique. Each of these wavelength channels has a fixed bit rate (e.g., 2.5, 10 or 40 Gbps). In contrast to optical burst switching and optical packet switching, optical circuit switched networks switch complete wavelength channels from an input fiber to an output fiber, without caring about the content of these wavelength channels. Note that this includes both opaque (with opto-electro-optical (OEO) conversion) and transparent (without such OEO conversion) switching operations. A Micro Electro-Mechanical Systems (MEMS) switch fabric is e.g. just one option to perform this transparently.

The remainder of this paper is structured as follows. Section II discusses some control plane related issue. Section III studies the problem of optimizing the routing and wavelength assignment in optical networks. Section IV investigates how the optical layer can act as a server layer to a logical client network. Section V discusses how Virtual Private Network (VPN) services can be offered in optical networks. Finally, section VI summarizes the paper. Despite the impressive work carried out in the COST action 266, not all relevant issues have been resolved. Therefore, each section also shortly discusses the remaining open issues and opportunities for further research concerning the topic(s) investigated in that section.

II. Network Control

Recently, extensive research and standardization work (in the IUT-T, IETF and OIF) has been conducted in order to make the optical network layer more flexible by introducing a distributed control plane and creating the so-called automatic switched optical transport network (ASTN/ASON). Due to the popularity and success of IP and MultiProtocol Label Switched (MPLS) networks, extending the MPLS control protocols towards the optical network is seen as one of the most promising options available, since it may ease the inter-working between the optical network and the client IP/MPLS networks. In Generalized MPLS (GMPLS), under development by the IETF [2], wavelength or timeslot toggling can be treated as generalized label switching. There exist several control plane models for IP-over-WDM networks [3]. In the overlay model, both layers have an independent control plane. The peer model integrates both control planes into a single integrated control plane controlling both layers, which is mainly favorable from a technical perspective. Addressing the problem also from the administrative perspective, the augmented model provides a compromise between both extremes [4].

In order to enable more advanced and flexible provisioning scenarios of a global reach (e.g. bandwidth trading, dynamically provisioned re-configurable virtual networks of global reach), domains of different Automatic Switched Optical Network (ASON) providers will need to inter-work.

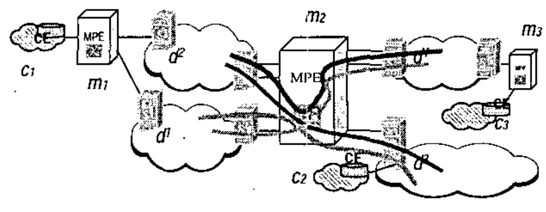

Figure1. Multi-Provider Edge model

For this purpose the novel Multi-Provider Edge (MPE) architectures [5] (see Figure 1), incorporating dynamically provisioned inter-domain interconnections, and leveraging flexibility of peer and augmented interconnection schemes, has been proposed and studied within the COST action 266. More precisely, the MPE overlay acts as a middle tear between providers and customers, and the providers themselves, attempting to address problems of providers reluctant to share their internal link information. For this purpose, the MPE acts as a trusted mediator, collecting and customizing information.

As an alternative to the above discussed GMPLS-based optical control plane, an Optical Private Network to Network Interface (O-PNNI) control plane (an extension of the well-known PNNI in ATM [6]) has been studied within the COST action 266. Both control plane models have technical pros and cons (summarized in TABLE I.), and both need many extensions and adaptations because neither of them completely supports all the optical control plane requirements. Apart from technical features and requirements, the final decision will depend on political and economical aspects.

TABLE I. COMPARISON BETWEEN GMPLS AND O-PNNI

CONTROL PLANE REQUIREMENTS	GMPLS	O-PNNI
Addressing	Yes	Yes
Connection Admission Control	No	Yes
Hierarchical structure	2 levels	Up to 104 levels
Separated control and data plane	Yes	No
Service Discovery	No	No
Path selection with QoS	Yes	Yes

Until now, the conducted studies with the MPE model focused on the effects of improvement of the blocking probability of the services (single-domain and multi-domain VPNs) in the multi-layer (TDM/WDM) network for different strategies of 2-layers routing and resource sharing. Future research will focus on the control plane architecture components, their functionalities and the way they organize in the distributed MPE overlay to support the augmented interconnection model.

Future research should also focus on improving the O-PNNI to support all the optical control plane requirements. This improvement will consist of:

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- Specifying which parameters exactly have to be advertised within a proposed PNNI Topology State Element (PTSE) in order to disseminate both optical and non-optical network information throughout the hierarchical structure.
- Adding signaling information to support a separated control and data plane
- Supporting service discovery to allow transport service characteristics to be queried before a connection establishment takes place.

III. Routing and Wavelength Assignment

Setting up a connection through a WDM network involves searching the route to be followed by that connection and the wavelength(s) to be assigned to that connection. In Wavelength Routed (WR) networks, the connection is assigned one wavelength from ingress to egress, while in a Wavelength Translating (WT) network, intermediate network nodes are able to convert the wavelength of an incoming channel into another wavelength. By optimizing the Routing and Wavelength Assignment (RWA), one is for example able to minimize the overall network cost. The goal of this section is to study different RWA algorithms and techniques.

In a first case study, two novel RWA algorithms have been compared with each other. The first one, TABUCOL [7], searches the shortest path based on a routing weight that increases with an increasing number of occupied wavelength channels on a link. The second one, called Minimum Hop RWA [8] searches all disjoint shortest paths and selects the less congested one. Simulations for both algorithms have been done on several network topologies. Both provide satisfying results. It was shown that the former one performs best in case of a rather high number of wavelength channels per fiber, while the latter performs best in case of less wavelength channels per fiber. It was also found that the use of wavelength converters would often not reduce the number of required fibers.

In order to deal with dynamic traffic in the optical network, the BYPASS Based Optical Routing (BBOR) technique [9] has also been proposed and studied. This technique reduces the signaling overhead by flooding new link states after a fixed number of wavelength channels changed their status and provides bypass routes to circumvent potential blocking on links defined as being congested.

In a second part, the RWA-problem has been extended to incorporate network recovery. Several options exist to perform optical layer protection in mesh networks. It has been shown within the COST action 266 that the capacity efficiency of shared-span protection and p-cycles [10] is comparable to that of shared path protection [11]. p-Cycles differ from shared protection rings in the sense that their backup resources are not only dedicated to protect on-cycle but also straddling links, as is illustrated in Figure 2. The capacity efficiency of other recovery schemes such as dedicated path protection and m:n protection was also investigated. The results showed that their capacity efficiency is comparable but is significantly higher than that of the previously described recovery schemes

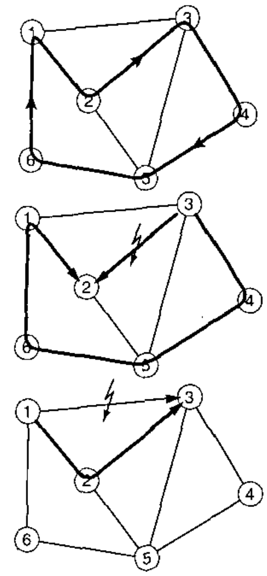

Figure 2. P-cycle protection. From top-to-bottom: network with established p-cycle, failure of an on-cycle and a straddling link.

(shared-span protection and p-cycles). Finally, dedicated span protection requires the highest amount of spare capacity. It was also found that the wavelength continuity constraint in networks without wavelength converters severely impacts the capacity efficiency of p-Cycles. Not only the impact of network recovery in meshed networks was investigated, but also a heuristic has been developed to design multi-ring networks.

A last case study dealt with the uncertainty in the forecast of the future traffic demand. It was shown that the impact of the uncertainty – modeled as a probability distribution function – on the expected traffic volumes may become very large, when a tight confidence interval is considered (see Figure 3).

Future research concerning the RWA problem will focus on both extending the BBOR mechanism to be applied to optical networks with conversion capabilities and including the BBOR mechanism when generating new routing strategies which integrate both the IP and optical layers.

The investigated RWA algorithms TABUCOL and Minimum Hop RWA also did not take into account any restoration issues, which would be interesting to include with respect to the achieved performance. Future work will focus on the impact on the blocking probability of conversion capabilities in the network when the BBOR mechanism is applied. Taking into account the available signal and switching capabilities of optics, new protection schemes specifically tailored for to WDM layer should be developed. Efficient heuristics are needed when an ILP formulation is not tractable. The robustness of the network design will be a key issue when the dynamic of the traffic pattern in the transport networks increases.

IV. Multi-layer IP-over-WDM Networks

IP networks, currently being enhanced by MPLS, will in the very near future become the main client of the optical transport network. In IP-over-WDM networks, the network can consist of an IP Point-of-Presence (IP PoP) node and/or of a WDM PoP node, as illustrated in Figure 4 [12]. The optical layer is said to act as server layer to support the client IP network layer. This means that the IP PoPs are interconnected with each other via connections through the optical network: in other words, these connections act as links in the logical IP topology. Most of the work presented in this section was dedicated to the study of techniques that allow optimizing the logical network topology. A distinction is made between static and dynamic techniques.

For the static case, a first case study showed that limiting the number of hops along the shortest path in the logical IP network may significantly increase the number of logical links needed in the logical IP network and thus also the number of required wavelengths in the underlying optical network [13]. In a second case study, it was shown that optimizing the logical network topology might imply a significant reduction of the overall network cost in an IP/GbE/WDM WDM (IP-over-WDM with Gigabit Ethernet in between) scenario, while it doesn't improve the network cost – compared to a fully meshed topology – in an IP/PoS/WDM (IP-over-WDM with Packet-over-SONET in between) scenario.

For the dynamic case, a first case study – dealing with SDH/WDM networks – showed that when a connection request cannot be supported by an existing lightpath, setting up a new lightpath for the connection leads to a smaller blocking probability than routing the connection over a chain of existing lightpaths [14]. By having an integrated routing strategy, allowing the connection to be routed over a chain of existing and new lightpaths, the blocking probability is reduced even further (see Figure 5). This case also showed the important impact of the fraction of installed transponders on the blocking probability.

In a second case study, the benefit of dynamically reconfiguring the logical IP network was illustrated [15]. It allows keeping the packet loss ratio reasonably low, while the physical resources are only used in case they are really needed. In addition to that, some other issues concerning dynamic reconfiguration of the logical IP network have been discussed, e.g., the need to introduce some inertia, in order to avoid instabilities.

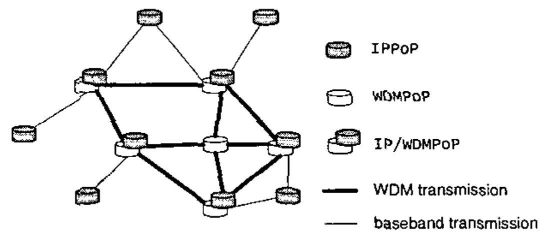

Figure 4. IP over WDM network structure

In a last case study, the impact of the typical asymmetric nature of the IP traffic has been investigated. This study showed that the higher the IP traffic asymmetry, the more beneficial it becomes to deploy unidirectional optical line-systems, compared to bi-directional line-systems (these last ones have the same amount of capacity in both directions) [16].

V. Optical Virtual Private Networks

Virtual Private Network (VPN) services are important in nowadays' networks. A VPN is a *virtual* network since it is not built physically and separately, but it is only a split and allocated part of resources of a public network of a provider (see Figure 6). It is *private* since it serves a closed group of users. Within the COST action 266, several methods for configuring optical VPNs were proposed, including protection alternatives as well.

Since the problem is very complex, it must typically be decomposed into smaller sub-problems, which can be solved

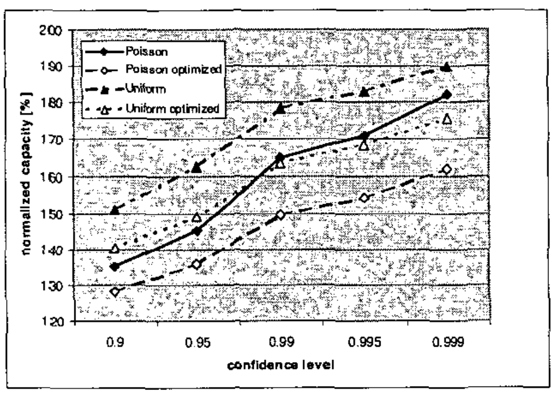

Figure 3. Required capacity for different confidence levels

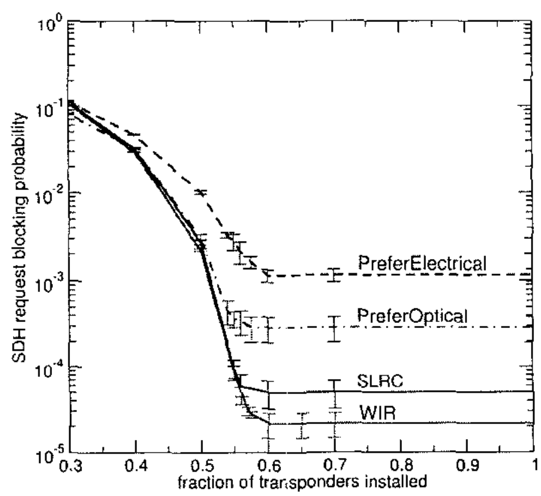

Figure 5. Blocking probabilities in a SDH/WDM network

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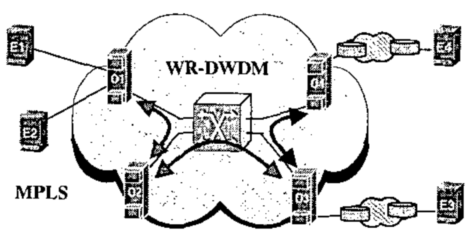

Figure 6. Illustration of the principle of an OVPN

for networks of practical interest. One of the most useful decomposition strategies is to route the demands one-by-one sorted according to their bandwidth requirements and distances, as well as to apply a link-cost scheme, that prioritizes use of wavelengths and links already used by demands of the considered VPN [17].

The demand-by-demand decomposition allows use of any other method for routing and wavelength assignment or protection described in other sections of this paper.

All these results are applicable to single layer static and dynamic networks such as OTN and ASON as well as to multi-layer networks.

VI. SUMMARY

This paper provides an overview of the main topics concerning optical wavelength/circuit switching networks, studied within the COST action 266 "Advanced Infrastructure for Photonic Networks".

First, in the architectural context different optical control plane models were studied, ranging from the overlay to the peer model, as discussed in this paper. Further, we explained how the need for flexible provision scenarios of global reach, motivated the development of a Multi-Provider Edge architecture with dynamic inter-domain interconnections. This paper also provides a comparison between PNNI and GMPLS control plane approaches.

A second important topic that was studied within the COST action 266 and that still receives much attention in current optical network research, are efficient (dynamic) routing and wavelength assignment schemes. Several schemes were discussed in this paper and compared with each other.

As IP networks are envisaged to be the main clients of optical transport networks, a third topic that was discussed in this paper deals with IP-over-WDM networks. Most of the work focused on techniques to optimize the logical IP network topology. Both static and dynamic techniques allowed obtaining good results. Also the influence on the overall network cost of the asymmetric nature of IP traffic was shortly discussed.

Finally, the work carried out on Optical Virtual Private Networks was described.

ACKNOWLEDGMENTS

The authors would like to thank the European Commission for funding this work, and the partners of the COST action 266 for the interesting and stimulating discussions. D. Colle would like to thank the IWT for its financial support for his postdoctoral grant.

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