SURVEY PAPER Special Section on Feature Topics on Latest Trends in Optical Networks

Optical Networks Functional Evolution and Control Technologies

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SUMMARY In this paper the current trends in the optical networking including the physical components, technologies and control architectures are discussed. The possible interaction schemes and implementation models of the automatic communication between applications and network as well as between ASON/GMPLS based network domains are proposed. Finally, the related research activities based on simulation results of control plane dimensioning are illustrated and real test bed experiments on OIF worldwide interoperability demonstration and the ongoing European IST project MUPBED are disseminated.

key words: optical network, control plane, ASON, GMPLS

1. Introduction

In recent years, optical data transmission technology has undergone tremendous evolution. Starting with unrepeated point-to-point transmission systems in the early 1980s the inventions of Erbium Doped Fiber Amplifiers (EDFAs), Wavelength Division Multiplexing (WDM) and the application of Reconfigurable Optical Add/Drop Multiplexers (ROADMs) and Optical Cross-Connects (OXCs) have led to an explosion of system capacity as well as of network functionality and extension. The next generations of meshed WDM networks are required to handle large amount of traffic at reduced cost and complexity. So the interconnected nodes should be transparent, reconfigurable and flexible to route traffic without loss at a single channel granularity.

Beside this technological evolution the network management and automatic control issues are also raised to a higher importance, since the daily operation and maintenance of these optical networks are become critical. The basic control architectures are based on the International Telecommunication Union — Telecommunication (ITU-T) G.ASON (Automatically Switched Optical Network) Recommendation [1] and the Internet Engineering Task Force (IETF) Generalized Multi-Protocol Label Switching (GMPLS) protocol suite [2].

In case of planning and/or dimensioning of WDM based optical networks, the layered transport network architecture is a valuable concept in order to simplify not only the design and operation, but also reliability and Quality of Service (QoS) assessment of these networks. Basically, the transport layer can be divided into three layers: circuit or packet layer, path layer, and transmission media layer. The path layer plays key role in constructing scalable, reliable and resilient network.

Looking to the Internet Protocol (IP) based client network, this layered architecture seems immortal because packet switch networks have begun to ingest the part of path layer concept by specifying Multi-Protocol Label Switching (MPLS) protocol and Label Switched Paths (LSPs) [3] as increasing demand of the QoS from network users. The LSP is logically defined path traversing Label Switched Routers (LSRs), which is similar to the concept of the virtual path in Asynchronous Transfer Mode (ATM) network. In order to enhance the capacity of the logically defined path, the concept of optical path or Optical LSP [4] is increasingly attractive, considering the recent progress of optical components and device technologies.

In the followings the current trends on the optical networking including the physical components, technologies and control architectures are discussed, and then the possible communication schemes between applications and network as well as between network domains are proposed. In the next section the related research activities are illustrated based on simulation results and real test bed experiments, finally we conclude our work.

2. Trends in Optical Networking

The main drivers of the current dynamic evolution of optical networking (including optical switching technologies) come from the well known fact that the traffic growth generated by the dominated IP client is not longer slow and predictable. However, not all the traffic is mission critical as it was in case of traditional voice and private-line traffic, and the optical transport technology is not restricted only to the long-haul static transport links, but becomes the key factor of dynamic metro and access network environment, as well.

2.1 Available Optical Components and Its Market Trend

The analysis on current optical equipments has highlighted

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a number of basic optical components, which can all be realized by several implementation options. The basic components and implementations [5] are the following:

- Couplers as basic input/output optical components.
- Mux/demux; can be realized using Arrayed Waveguide Gratings (AWGs) or diffraction gratings.
- Wavelength Blockers (WBs) and Variable Optical Attenuators (VOAs); are obtained exploiting liquid crystals, Micro Electro Mechanical Systems (MEMS), or Planar Lightwave Circuits (PLCs). But they can also be realized through the use of tunable filters built on Fiber Bragg Gratings (FBGs), PLCs or MEMS [6].
- Switches; can be obtained using Semiconductor Optical Amplifiers (SOAs), MEMS or PLCs.

Note that recent research activities on optical switching technology have proposed new switching devices such as micro-ring resonators, organic materials for switching structures, micro-optical waveguides, Raman amplifiers among others [5]. The aforementioned basic functions are the main components of the complex optical devices such as WBs and Wavelength Selective Switch (WSS); integrating mux/demux, blocking and power equalization as well as switching functions.

Nowadays, functionality integration seems to be the frontier because of the major requirements on cost reduction. In this context, the WSS seems to be the most promising architecture for ROADMs and OXCs. They have the ability either to switch any channel in a WDM stream from an input fiber to different output fibers, or vice versa to multiplex many WDM channels from separate inputs into a single output, with a very low insertion loss [5].

According to the current market trends on optical components the three most important optical modules are ROADMs, EDFAs and widely tunable transponders. A dramatic rise in ROADM sales (including WSS) in 2005 marked the beginning of a pervasive generational change in Dense WDM equipment. By the end of 2006 ROADMs are on track to exceed fixed OADM sales. Full-band tunable transponders are also displacing traditional interface modules and next-generation EDFAs will become the largest amplifier type in 2006. Next-generation EDFAs are those designed explicitly to support large power transients as the number of wavelength channels [6].

2.2 Evolution on Network Control Architectures and Protocols

The optical technology is reaching a maturity status that allows starting to think about the functional extension of the optical network layer. Following to above technical trend, the IETF has extended the Constraint-Route based Label Distribution Protocol (CR-LDP) and Resource reSerVation Protocol for Traffic Engineering (RSVP-TE) [7] to realize intelligent control of the optical paths in the ROADM and/or OXC based networks. The specification of these extensions called GMPLS [2] protocols. GMPLS specifies the unified network control scheme not only for the MPLS LSPs and optical paths, but also Synchronous Digital Hierarchy (SDH) Time Division Multiplexed (TDM) paths, fiber paths and so on. Therefore, the deployment of the GMPLS protocols provides significant opportunity not only to construct interoperable multi-layer network with low operational cost, but also to unify the network management systems of variable networks [8].

In parallel with the IETF activities on GMPLS protocol suite (i.e. routing, signaling and management protocols), the ITU-T defines the recommendation on ASON based control architecture [1] basically independently from the protocols applied. ASON segregates the networking functions within each layer network into three logical functional planes: control plane, data plane and management plane. They are responsible for providing network control functions, data transmission functions and network management functions, respectively. The crux of the ASON network is the networking intelligence that consists of automatic routing, signaling and discovery functions to automate the network control functions.

Nowadays, the widely used term “ASON/GMPLS” [9] refers to a control architecture designed according to the ASON overlay architecture and exploiting GMPLS technologies and protocols for the control processes. Among the advantages of the ASON overlay model over the GMPLS peer model, there is the fact that it is the one of practical for near-term deployment, as it requires limited “vertical” interoperability. On the other hand, it offers high flexibility with respect to administrative or business models, since it can be used in a single administrative domain covering both the packet and the optical layers, as well as in contexts where the packet and optical networks are operated and managed by separate entities. Note that the ITU-T also supports the augmented model [1], while IETF supports the augmented and overlay model as well [10].

3. Application Driven Optical Networks

Service provisioning in traditional static optical networks requires human interactions, where e.g. a client emails or calls a network administrator who sets up the required connection in the circuit switched transport network manually. The authentication and authorization are based on manually obtained agreements. Such path establishment is not in the second or minute time scale; rather in weeks and months. If the connection is a multi-domain connection, the client should contact each of the involved network administrators or the first administrator should contact the next in the connection sequence. This further complicates the connection setup and the time consumption is significant.

In dynamic optical networks, communication protocols help the interaction between the client application and the transport network as well as between the different network domains. ASON/GMPLS is seen as a key enabling control technology providing ways for horizontal and vertical network interconnection and network integration. Coordina-
tion between the network elements is achieved by exchanging control plane information by means of suitable protocol communication actions over the defined signaling connections and reference points. The reference points; User-to-Network Interface (UNI) and the External Network-to-Network Interface (E-NNI), are defined by the ITU-T and the Optical Internetworking Forum (OIF) [11], as an industrial forum, supports their implementation. The overall goal of the OIF is to complete one interoperable, harmonized set of ASON/GMPLS standards and specifications to foster the deployment of control plane enabled optical networks [11].

3.1 Communication Schemes between the Application and the Network

The typical client applications of the dynamic optical networks (e.g. uncompressed video transmissions, content and storage applications, data grids, etc.) usually do not communicate on a UNI level. This is mainly because a separation of applications, network layer protocols (e.g. RSVP-TE, CR-LDP) and interfaces (e.g. IETF GMPLS UNI, OIF UNI) is required by the application developers who need a higher level of abstraction. Hence, an adaptation function can be introduced as responsible for interfacing with the optical control plane and for deciding when new network resources from the circuit layer should be established. The adaptation function receives proprietary resource requests from the applications and is responsible for triggering these resources in the network based on the standardized UNI protocols. The adaptation function includes functions for manipulating the circuit layer by requesting setup of new and release of existing connections. The manipulation can be driven by application requests or by long term monitoring of optical link utilization and prediction of the most optimal usage parameters.

3.1.1 Adaptation Function and Implementations

In general, the applications, acting as clients, communicate with the adaptation function through an Application Programming Interface (API), which can be implemented as a web service. At the application side only a simple modification is needed; the implementation of the Network Service Requester (NSR) component which handles the requests [12]. Actually, the implementation of adaptation function follows three different tracks (Fig. 1):

- Light stack
- Standalone
- Socket

The light stack implementation is developed as collection of modular functions. The main tasks performed by the stack are the translation of the requirements on the application-side into the appropriate parameters on the network-side, the resource admission control and allocation.

The standalone implementation includes the resource allocation function itself, but it is not integrated directly with specific applications. It provides a Graphical User Interface (GUI) as a small client to the user, and this client integrates the NSR. This approach can be used e.g. for the high quality uncompressed video transmissions, which is a professional and commercial application, where it is not possible to integrate the NSR.

In the socket stack the applications do not communicate through an API. Instead, they directly execute socket calls in the UNI client side (UNI-C) proxy. No bandwidth reservation planning mechanisms are provided, the application can just request bandwidth and the request will be fulfilled (or not) immediately. The advantage of such a solution is that this implementation can avoid possible setup delays related to complex calculations in reservation functions. However, this approach requires that the application is implementing additional communication protocols (i.e. UNI protocols) to be able to talk to lower layers of the adaptation function.

3.2 Communication Schemes between the Network Domains

Linking two separated network domains with different control architectures requires an intermediate solution which will be capable of translating one format of control plane messages to another. An obvious intermediate solution can be an UNI Proxy server [13]. This proxy is planned to be able to translate between ASON and GMPLS control plane messages. UNI Proxy is essentially a hardware component on which RSVP Agent is running. RSVP Agent is an application which can communicate using the RSVP-TE protocol. The RSVP-TE protocol can be implemented according to the IETF and the OIF specification, as well. The minor difference between them is only the message format. These two versions of RSVP-TE protocol define control plane communication in GMPLS and ASON network, respectively, thus making it possible to establish connections traversing both heterogeneous domains. Therefore, UNI Proxy will act as a mediator or agent between two heterogeneous networks (Fig. 2(a)).

The benefits of UNI Proxy agent solution are twofold. On one hand, it solves the required communication between the ASON and GMPLS control planes, and on the other
3.2.1 Inter-Working between Packet and ASON/GMPLS

domains

hand it is also capable of connecting the pure IP/MPLS or
pure Ethernet networks with GMPLS capable centralized
management to the ASON/GMPLS based domains with dis-
tributed control functions. The MUPBED project’s experi-
mental results proof both solutions but the shortcoming of
the multi-domain RSVP-TE protocol has to be solved in the
next step.

3.2.1 Inter-Working between Packet and ASON/GMPLS
Domains

Today’s client networks are traditionally IP based and are
adopting or are going to adopt MPLS and its traffic engi-
neering features. Inter-working between IP/MPLS domains and
ASON/GMPLS is therefore of extreme importance. The one
of the inter-working issues have to be solved for intercon-
necting MPLS-based packet networks and GMPLS-based
optical transport networks is to decide inter-working archi-
tecture, such as peer-to-peer, overlay or augmented [13].

Because of the quick spread of pure switched Ethernet
networks, thanks to its simplicity and low cost, it is also an
interesting research area to investigate the possibility to con-
nect pure Ethernet with ASON/GMPLS domains. In prac-
tical case the RSVP Agent can be run on gateway equip-
ment (e.g. UNI Proxy) connected to both ASON/GMPLS
and Ethernet network. The UNI Proxy has to communi-
cate with proprietary Ethernet management applications e.g.
based on Virtual Label Switch controllers [10]. The applica-
tion itself acts like a centralized Ethernet control by manag-
ing virtual local area networks (VLANs) as Ethernet paths
(Fig. 2(b)).

The proxy should also contain a data re-labeling func-
tion between the GMPLS and the proprietary Ethernet la-
bel. Currently, the main question is the proper GMPLS la-
bel definition for Ethernet. There are six different proposals
[14]; inserting MPLS label (i.e. Shim header or MPLS Eth-
ernet type), using proprietary MAC address, using VLAN
ID plus destination MAC address, and finally using new Tag
Protocol Identifier (TPID). The Shim header is preferred by
IETF, and there are implementations with new TPID as well.

In conclusion, cooperation of these two applications
(Ethernet management and RSVP Agent) makes the cre-
ation of paths in heterogeneous networks possible.

4. Survey of Related Research Activities on Optical
Network Control Technologies

Now it has became evident that the only way towards the
functional evolution of the optical networks is the imple-
mentation of optical control plane based on different archi-
tectures, and the application of inter-working functions be-
tween the different domains to establish end-to-end service
provisioning.

Currently, a strong effort is being done to standard-
ize interfaces for GMPLS-based and ASON-based network
inter-working. For these reasons, intensive tests are of ma-
jor importance before a network operator could rely on these
interfaces. First of all, it is necessary to perform control
plane dimensioning and simulation tests in order to assess its
scalability, performance and behavior, as well as the impact
on the overall network before a control plane is deployed.
Then, network demonstrators and field trials must be imple-
mented in order to assess both the new network elements
and the impact of the GMPLS control plane.

4.1 Illustrative Simulation Results

Boundaries on delay, guaranteed bandwidth and low packet
loss are some of the requirements by future high demanding
applications of optical networks. To accommodate these de-
mands, it is necessary to reserve resources in the network for
the specific applications, whether these require QoS in the
presence of paths in heterogeneous networks possible.

In Fig. 3, it can be seen that in a control node the sig-
aling delay (i.e. the time while the signaling message has
been processed) is highly depends on the load of the sig-
naling system [15]. In the simulations the assumptions on
the statistical behaviour are; the signalling message’s arrival
process is Poisson, the message processing time is expo-
nentially distributed (modelled by M/M/1 queue), the mes-
sage transmission time is deterministic (modelled by M/D/1
queue) and the link delay is constant. The 100% system
load means that the number of unprocessed messages in the
queues is starting to increase infinitely, i.e. the system is get-
ting to an unstable state [15].

The UNI Proxy solution with out-of-band signaling
transmission and software based signaling procession is ap-
plied as reference. This provides the highest delay in a

Fig. 2 (a) ASON-GMPLS inter-working by UNI Proxy, (b) inter-
working with packet domains.
given system load. Some vendor implementations on control plane (e.g. Alcatel, Transmod, and Juniper) apply in-band signaling transmission which provides lower delay in low loaded networks. The application of hardware accelerated signaling processors and out-of-band signaling transmission becomes better than the in-band solution in case of high loaded signaling networks.

If out-of-band, out-of-fiber signaling networks are used the other question is the reliability of this separated signaling network. The main requirements on the reliability are defined by IETF IP over optical working group [16]:

• The optical control plane signal network shall support protection and restoration options.
• The signaling control plane should implement signaling message priorities.
• Control network failure detection mechanisms shall distinguish between control channel and software process failures.
• Fault localization techniques shall be supported.
• Partial or total failure of the control plane shall not affect the existing established connections.

Regarding the last bullet point, the OIF’s and the ITU-T’s statement is the same; a signaling channel failure must not result in the release of established connections. In simple words it means that during the outage of the signaling network the already established switched connection services are stuck in the network which has impact on the optical network performance. A proposed solution which can minimize this effect is an adaptive signaling message routing [9] which takes into account the optical paths and the spare resources, as illustrated in Fig. 4.

In the given optical network topology (incl. 19 nodes and 28 links [9]) an out-of-fiber signaling channel failure is simulated and the blocking probability of the new optical connection requests is measured. In the first case the associated signaling messages were routed along the physical data paths (i.e. the controlled optical working paths), in the second case along the protection paths and in the third case along the optimal paths which are the most diverse form the associated physical connection’s paths. The blocking probability was the lowest in the third case. If the average number of the optical connections controlled by signaling messages routed on the same signaling channel are increasing the network performance is decreasing (i.e. the blocking probability of the new connections is higher) in all the three cases [9].

4.2 Dynamic Ethernet and SDH Service Test Bed Experiments

In the followings ongoing implementations and some examples are shown on recent interoperability test in Europe, Japan and, of course, worldwide.

4.2.1 2005 OIF Worldwide Interoperability Demonstration

The OIF demonstrated the worldwide dynamic Ethernet and SDH call set up and tear down services in conjunction with SuperComm2005 held in Chicago on June 7–9, 2005 [17]. In this demonstration, equipments from 13 vendors were used and located in 7 carrier laboratory facilities around the world. The demonstration utilized a distributed control plane based on OIF Implementation Agreements to control an SDH transport service (UNI1.0R2), an Ethernet over SDH adaptation (UNI2.0), and transport over multiple domains (E-NNI).

The Signaling Communication Network (SCN) was constructed between carrier’s laboratories over the public Internet. This SCN was used for signaling and routing information exchanges. Virtual data link connections and few real data link connections were established among carriers. The overall topology and an example of active Ethernet and SDH calls are shown in Fig. 5.

To build a live view of the active calls, a custom software application was used. An agent application which intercepted signaling and routing messages sent over the SCN was installed in each laboratory. The agent analyzed updated information from messages and sent this local site information to a master server application on the SuperComm show floor. The master server application built global topology views every 15 seconds. These views were available via Web interface. An example of carrier’s laboratory site
4.2. NTT Site Configuration and Findings

NTT provided Musashino R&D center and Yokosuka R&D center as an NTT site during the demonstration. The equipment from Avici, Fujitsu, Sycamore, and NTT’s prototype systems was used. Avici provided UNI-C devices for UNI1.0R2 and UNI2.0. Fujitsu and Sycamore provided UNI network side (UNI-N) devices with E-NNI capability which supported Ethernet over SDH function and SDH transport function. There were two types of NTT’s prototype systems. One was provided UNI-C function. Another was provided UNI-N function which was based on a Lambda Switch Capable (LSC) device; i.e. optical switches. These boxes provided Ethernet and SDH over wavelength transport function. The configuration at the NTT site is shown in Fig. 6.

In the demonstration, an inter-site connection point was constructed in the Musashino centre and connected to AT&T, China Telecom, and Deutsche Telekom by 2.5 Gbps SDH virtual data links. Several Ethernet calls (from 150 Mbps over VC4-1v to 1 Gbps over VC4-7V) were set between other carrier laboratories. Regarding NTT intra-site connection, three Fast Ethernet links were set between Musashino and Yokosuka to construct the SCN as shown in Fig. 7. One Gigabit Ethernet link was also set for the data link. These Ethernet links were constructed over NTT’s test bed network named ‘GEMnet2’ [18] by using an Ethernet over MPLS over ATM technology. We designed the NTT intra-site SCN architecture so as to make it possible for the agent application described in the previous section to collect all signaling and routing messages both in Musashino and Yokosuka. To do this, an Ethernet switch with port monitoring function was located in Musashino, and the agent application was acted as the proxy of all NTT sites. As shown in Fig. 5, the configuration of the NTT site was successfully included in the global topology display for demonstration purposes.

In the period of OIF demonstration, NTT also performed intra-site evaluation such as Ethernet call establishment, and ASON/GMPLS interoperability with various types of service classes based on hierarchical signaling architecture. The ASON based RSVP-TE signaling from UNI-C devices is sent over the Forwarding Adjacency (FA) LSP within the GMPLS domain established between two UNI-Ns. UNI-Ns act as the gateway between the ASON and the GMPLS domains. NTT successfully confirmed ASON/GMPLS interoperability for unprotected class and shared-mesh restoration class optical path creation, where each service class was directly assigned from UNI-C routers [19].

4.2.3 Interoperability Demonstrations in IST Project MUPBED

In the European IST project MUPBED [20], the horizontal and vertical integration of networks and applications are considered for multi-domain heterogeneous networks. Horizontally, five test beds are interconnected through GEANT2 network to evaluate ASON and GMPLS technologies and vertically a number of applications has been selected and modified in order to automatically request resources from the network (Fig. 8). A key objective of the project is en-
abling seamless inter-working among these domains.

In the pure switched Ethernet domain the interconnection of an Ethernet core network and a GMPLS based network can be accomplished with the implementation of a software-based RSVP agent that is used to translate path reservation messages, ad so on. In the pure IP/MPLS domain an IP/MPLS infrastructure is constructed using devices like routers, servers and clients and protocols like OSPF, MPLS, etc. and then the control plane scenario, based on a GMPLS UNI solution, will be set up. In the GMPLS domain, the control plane interconnections will be achieved by means of GMPLS UNI run over the existing layer 2 interconnections between the domains. The control channel is therefore in-band and separated from the data.

In the ASON domain the control and data planes are clearly separated and the UNI signaling on the edge equipment of the ASON domains can be realized either in-band or out-of-band through a separate IP network [13].

With use of UNI Proxy implementation in the ASON domain the control plane in the project making them a part of MUPBED’s common control plane [13].

5. Conclusions

In conclusion, both the optical technologies maturity and the introduction of an ASON/GMPLS control plane support the migration of capacities from the IP to the optical layer. This migration would enable cost reduction, support innovative services, multilayer network integration and, in general, implement next generation agile transport networks, able to cope with the threats and increasing pressure on the network operators. Anyway, the necessity of supporting legacy services with important revenues makes a global migration to ASON/GMPLS networks difficult. The expected roadmap is a gradual and slow introduction of the control plane procedures in the transport networks.

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References

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