An Integrated Network Management Approach for Managing Hybrid IP and WDM Networks

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Abstract

Pacing toward converged voice and data networks, the IP over WDM/OTN network architecture supported by MPLS satisfies the advanced next-generation network requirements to provide fast, reliable, and flexible connectivity services. Acknowledging the advantages of networks that utilize the above technologies, operators evolve their networks in that direction, while continuously working to provide new services to attract customers. In their effort to facilitate such services in a flexible and cost-effective way, an integrated network management system for IP and WDM technologies is a prerequisite. This article proposes a management architecture that provides for this integration. Different approaches to integrating multilayer networks are briefly described covering both the control and management planes. The adopted solution is based mainly on the management plane utilizing the control plane wherever possible. Additionally, preliminary results from the evaluation of the configuration management functionality of the proposed system in a testbed environment are presented, concluding with future extensions that also cover fault and performance management.

In recent years the telecommunications market has expanded and diversified dramatically. New network and service providers have entered the market, and competition has sharpened strongly. On one hand incumbent operators already feel the pressure of competition and are trying to minimize their operational costs, at the same time optimizing their network architecture and exploiting their legacy infrastructure as much as possible. On the other hand, competitive newcomers are deploying new intelligent network solutions as a means to claim a share of the market. Such solutions are usually based on the latest advances in technology, but there is always a high risk of investing in immature and not fully validated solutions. Besides, the recent market slowdown has cleared the telecom field, leaving only a few strong players in the market, incumbent or competitive, which are trying to reengineer their business strategies.

The evolution path toward the next-generation IP over optical networks will be facilitated by the generic framing procedure (GFP) standardization [1], providing a flexible adaptation layer to carry packet data over a synchronous optical physical layer. Regarding the interplay of the two technologies, most trends propose the use of the control plane as a means to achieve integrated IP over wavelength-division multiplexing (WDM) service provisioning. However, standards are still on the way, and high-end optical products, like optical cross-connects with control plane, are too costly. Moreover, the business models for such interactions are not very strong and demand is relatively low, affected by the global telecommunications depression.

In light of these developments, this article proposes a different approach for the integration of IP and WDM technologies mainly using the management plane. This will be accomplished through an integrated network management system (INMS) capable of providing fast, differentiated, reliable IP over WDM connectivity services efficiently and affordably, mostly using management functions supported by control functions wherever applicable. The key idea is that as soon as advances in the control plane of IP and primarily in WDM become available, they can be exploited by the management plane until an integrated control plane becomes a reality. Even then, the integrated control plane can be triggered by the management system to provide additional features such as scheduling, which by definition is not supported by the control plane functionality. The provided connectivity services are supported by multiprotocol label switching (MPLS) label switched paths (LSPs) that are created over optical subnetwork connections (optical SNCs) or plain optical channels spanning the WDM network. Particularly, MPLS with the sup-

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port of different quality of service (QoS) parameters, derived from the service level agreements (SLAs) of the connectivity services, allows the provisioning of a differentiated set of connectivity services. In the rest of the article, the terms IP and MPLS will be used interchangeably to mean an IP network with MPLS capabilities. The advantages gained by deploying such management systems are obvious, facilitating the transition toward future networks while narrowing serious risks of insecure investment. In this context, network management is recognized by operators even more intensively as one of the key aspects in keeping a predominant position in such a severely competitive environment.

The path-based connectivity services provided by the INMS should also be backed up by the traditional fault, configuration, accounting, performance, and security (FCAPS) management areas as well as new features, like policies capable of influencing the system behavior. The latter allow the specification of rules that can be applied to the managed network, making the configuration of the network much simpler for administrators, who merely specify them by using a near physical language.

The structure of this article is as follows. We first give an overview of the different approaches to multilayer integration covering both the control plane and management plane approaches. We then describe the functionality and architecture of the proposed system solution, giving some implementation details as well. We also present the testbed environment used to perform our experiments, devoting a section to the assessment of the proposed system. Finally, a summary of the proposed approach as well as future extensions of the proposed system are given.

Multilayer Integration

The broadband integrated services digital network (B-ISDN) reference model defines three planes for telecommunications networks: the control, management, and user planes. This classification promotes the systematic study of networks since it allows distributing their complexity and focusing on the plane under investigation.

The control plane deals mainly with signaling messages for connection setup, and routing protocols that support automatic network discovery and protection mechanisms; it involves mainly real-time procedures. On the other hand, the management plane covers the FCAPS functional areas, some of which offer similar functionality to the control plane functions, while providing additional functionality such as scheduling and alarm correlation. The management plane is a near-real-time approach. The two planes do not share an equal stake in various types of networks. For example, IP networks mainly follow the control plane approach, whereas telecom networks, including WDM technology, follow the management plane approach.

In order to achieve multilayer integration most researchers have proposed extending the signaling mechanisms of IP networks to the optical layer and control the two technologies in an integrated way. This article outlines a different approach, proposing a paradigm that preserves the telecom-style approach in the optical layer and extends it into the MPLS layer for provisioning integrated path-based Internet services using mainly management functions and secondarily control functions. In the rest of the article, attention is given only to direct integration of IP/MPLS over WDM without any other intermediate layers (e.g., asynchronous transfer mode, ATM, or synchronous digital hierarchy, SDH). This assumption does not restrict the generality of the approach. A brief description of the control and management approaches follows.

Integration through the Control Plane

In [2] different business models, namely overlay, peer, and augmented, were proposed for the integration of multilayer networks. Of these models the overlay model is the one that allows easy migration from the existing situation to the deployment of optical network elements (ONEs) for the transport of IP directly over WDM. However, this model should only be considered as a short-term solution since it does not promote the integration of the control plane of the IP and optical networks. On the other edge is the peer model, which is a long-term solution and provides full integration of the two layers. In between lies the augmented model, which combines the advantages of the peer and overlay models, also shrinking their disadvantages.

In the scope of these three models, significant work has been done in the area of integrating the electrical world (IP) and the optical world (WDM). The most dominant achievements in the area are the automatic switched optical network/automatic switched transport network (ASON/ASTN) frameworks ([3, 4]) studied within the International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) and the Internet Engineering Task Force's (IETF's) MPλS/generalized MPLS (GMPLS) framework [5].

The ASON is based on the overlay model and extends the idea of an optical transport network (OTN), providing its client networks end-to-end optical channel connections in an automatic and fast way via the control plane. Two different reference points have been defined, namely the user–network interface (UNI) between client networks and the ASON, and the network–network interface (NNI) between routing areas in one administrative domain (internal NNI) or between different ASON administrative domains (external NNI). Additionally, the management NMI-A interface expedites the interaction between the management plane and the ASON control plane, while the NMI-T interface allows interactions with the network elements of the transport network. A generalization of the ASON framework to also cover other transport layers characterizes the ASTN framework, which describes the technology-independent requirements for connection setup across a transport network. Finally, it should be noted that the ASON/ASTN framework is generic enough and not bound to any particular signaling protocols such as the Resource Reservation Protocol with Traffic Engineering (RSVP-TE) or ATM Forum's private NNI (P-NNI).

In parallel, the GMPLS framework extends the MPλS framework, which is based on the peer model, to multiple layers. Existing Internet routing protocols, such as Intermediate System to Intermediate System (IS-IS) and Open Shortest Path First (OSPF), that are used under the MPLS framework protocols have been enhanced to disseminate information relevant to the optical domain, allowing their reusability in the new GMPLS framework. GMPLS focuses on the provisioning of MPLS LSPs over multiple layers and can be considered a superset of ASON with respect to the transport networks covered. Moreover, GMPLS is not restricted to the peer model and is extended to embrace the overlay or augmented models. However, its generality is questioned since it is bound to specific network protocol extensions: RSVP-TE and Constraint-Based Routing Label Distribution Protocol (CR-LDP).

Integration through the Management Plane

The idea of an integrated network management system, capable of managing heterogeneous networks also spanning different administrative domains, was always attractive for network operators, and significant research efforts have been expended in that direction [6]. Nonetheless, a closer look at the deployed

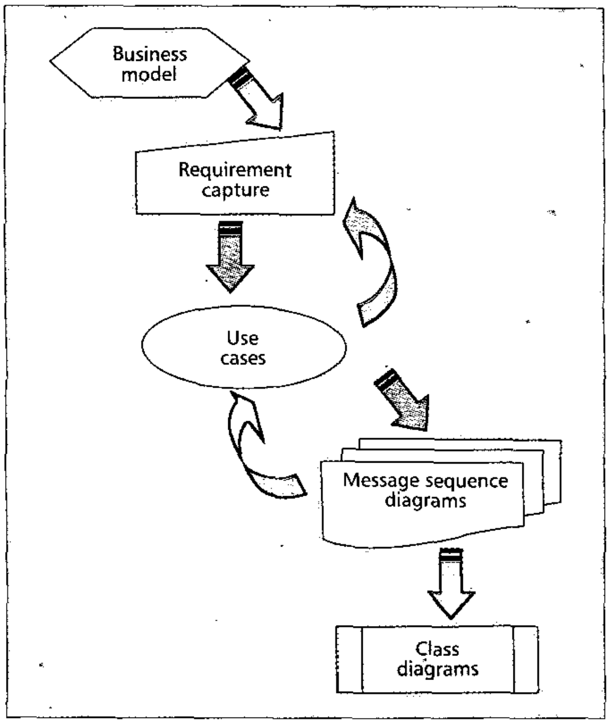


Figure 1. *System development methodology.*

network management systems of the majority of (especially incumbent) network operators proves that such systems, for the time being, are not deployed on a large scale despite their apparent advantages.

Operators are still using single network management systems that exhibit significant differences, especially between the management of IP networks and that of transport networks like SDH and WDM. For the management of recent transport technologies like WDM, traditional SDH management systems are extended in order to cover them. Thus, lightweight integration mainly in the areas of configuration and fault management is performed, supporting the integrated provisioning of end-to-end connections, integrated alarm reporting, and correlation capabilities. Multitechnology management integration, in terms of supporting full configuration and fault or performance functionality, is still under development in commercial product releases. Nevertheless, the recent standardization of the INMS southbound interfaces toward technological domain systems (IP, ATM, SDH, and WDM) and northbound interfaces toward service management systems (SMS) is one more reason for the development of umbrella network management systems wrapping around multiple single-technology domain management systems.

The TeleManagement Forum (TMF) has already moved in that direction by specifying transport-technology-independent common management interfaces from the element management layer (EML) toward the network management layer (NML), and from the NML toward the service management layer (SML) of the TMN architecture. The outcome of the above efforts was a series of documents providing among others, the multitechnology network management (MTNM) [7] and connection and service management information model (CaSMIM) [8] specifications.

The emphasis of this article is on the integration of IP and WDM, having as a keystone the management plane and gradually adding control plane building blocks of IP/MPLS or optical layers as they become available. This approach is considered a mid-term solution, allowing in the meantime development of control plane standards. It will also provide the needed time to validate the control plane implementations in real network environments, ensuring interoperability between different manufacturers' equipment. In the next section the adopted management plane approach is further analyzed.

Intertechnology Management Architecture

The Approach

The complexity of the problem requires a systematic approach in order to reach the proposed functional architecture, define the interfaces between the different components of the system architecture, and finalize the software design and implementation of the system. Part of this systematic approach was based on the Rational Unified Process (RUP) methodology with appropriate modification where necessary. Figure 1 depicts the five-step methodology (business model, requirements, use cases, message sequence diagrams, class diagrams).

First, the business reference model was identified by defining the different roles that may be undertaken by certain business entities, followed by the requirements capture phase. The requirements were categorized, elaborated, and prioritized until an agreeable and feasible set of requirements was achieved. Then, the use cases were specified. Use cases describe the interaction between the actors (both human and non-human entities) and the system under design. Since the set of use cases should cover all the requirements, there was a feedback from the use cases to the system requirements. Advancing to the next step, possible scenarios were identified describing interactions between the actors and the system, and within the system itself. These scenarios where specified, in a formal manner, using message sequence diagrams (MSDs). Finally, when MSDs were defined for all scenarios, leading to verification of the system architecture, class diagrams for every component (subsystem) were produced, kicking off the implementation phase.

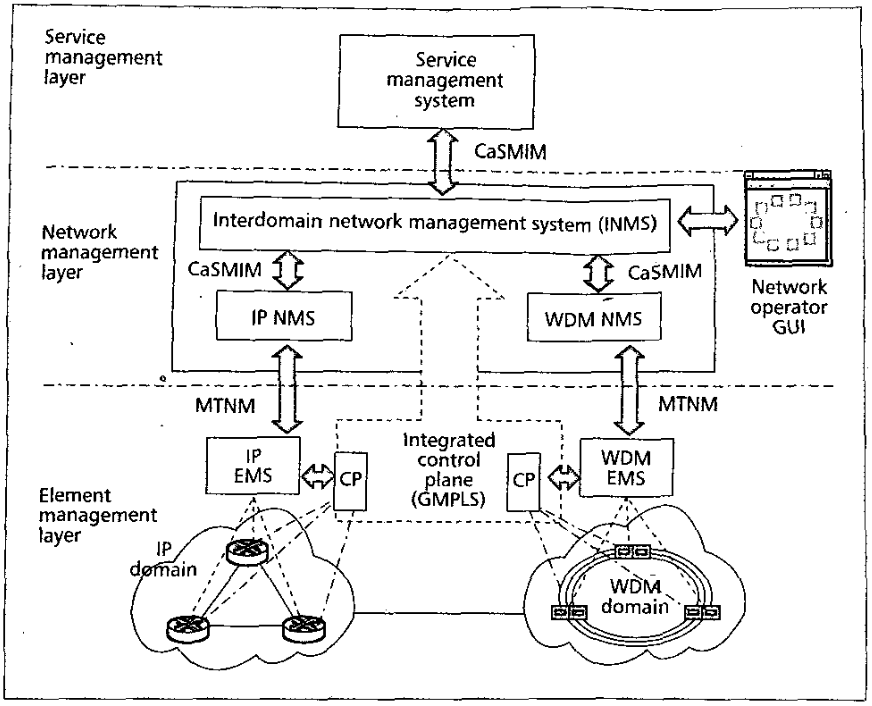
This five-step methodology allowed the specification of a quite complex system without compromising any functional characteristic, giving better insight to the system under development and preventing us from building a monolithic application that could not be modified or enhanced at a later stage.

System Functionality and Architecture

The main goal of the proposed management solution is to offer an open and scalable integrated network management system for the provisioning and maintenance of IP over WDM end-to-end transport services derived from SLAs. Secondarily, standalone lambda services (optical SNCs) can be offered to the network operator or customers.

Applying the methodology presented earlier, the following generic functional requirements were identified, covering three of the FCAPS management areas, configuration, fault, and performance:

- The configuration management functionality covers integrated provisioning tasks providing end-to-end views of connections along with their underlying infrastructure and facilities, independent of the technology. The basic requirement is the provisioning of end-to-end IP connectivity services (ICS) over optical SNCs using MPLS technology with QoS support. In this context the INMS is capable of calculating, designing, and creating MPLS LSPs over the corresponding optical SNCs in the optical layer, as a means of providing the requested ICS. These LSPs are realized triggering the IP control plane of the network elements for LSP provisioning with explicit routing (path selection) . Regarding QoS support, the target for the first prototype release was only bandwidth guarantees, while other QoS parameters (e.g., availability, delay,



☐ Figure 2. *System architecture.*

jitter, throughput, loss) are currently being implemented. In addition, no control plane has been used for optical SNC setup, since these building blocks were not available in the testbed.

• The fault management functionality involves the collection of faults across the different technologies, and determines the root cause and responsible faulty layer. Topology information and user-defined rules are applied to faults received from the NMSs' fault managers. The reporting of and recovery from faults in the IP or optical layer in an intelligent and integrated way are considered basic prerequisites. Reporting of automatic protection switching by the control plane, as well as notifications of primary faults through the INMS, is supported after the corresponding filtering, analysis, and correlation of the multiple alarms that are propagated by a single fault. The report includes all the attributes of the received alarms together with the list of affected LSPs. An automatic integrated fault restoration mechanism applies to restore all the affected LSPs triggered by the INMS after the integrated analysis and correlation of the propagated alarms.

• The performance management functionality includes the collection and processing of data from the technology NMSs in order to assess the performance of the network and the usage of resources. Based on these assessments the operator is able to perform proactive management of transport capacity across their multilayer network and prevent congestion (hot spots) affecting the offered connectivity services. The key precondition is the ability to monitor, filter, and report performance data. The INMS monitors the traffic and QoS network parameters of the LSPs and report service degradations in case of performance gauges' or counters' threshold crossings.

In the first software integrated prototype only configuration related functionality was tested. Fault and performance functionality, as well as additional configuration management tasks (further QoS support), will be added in future enhancements of the system.

Figure 2 depicts the overall high-level architecture of the proposed management solution. As indicated, the notion of the umbrella INMS is adopted situated on top of each technology NMS. The INMS can be considered the technology-independent network management sublayer of the TMN, while the NMSs form the technology-dependent sublayer. In principle, the INMS can communicate with more than one NMS belonging to a single technology, providing the system scalability as the number of networks that should be managed grows. In Fig. 2 a simplified image is depicted with only one NMS per technology.

The northbound interface of the proposed system architecture toward third parties' SMS application programming interfaces (APIs), as well as internal interfaces between the INMS and IP or WDM NMSs is based on the TMF CaSMIM [8] specification. The southbound interface of the two NMSs is based on the TMF MTNM [7] specification, which has been enhanced and specialized for the IP and WDM technologies. Moreover, the system southbound interfaces toward the network element layer are also based on the MTNM specification. The employment of published APIs, based on TMF's specifications, for the implementation of the system boundary interfaces provides for openness of the system, since any third parties have the possibility to implement their own management application exploiting the proposed system. At the same time, the proposed solution is flexible enough, being capable of both evolving and accommodating the continued operation of legacy and new systems.

No direct interaction between the IP and WDM NMSs is foreseen, and communication is performed only through the INMS in either a topdown (mainly for configuration management purposes) or bottom-up direction (mainly fault and performance management purposes). The IP NMS uses some facilities of the control plane of routers such as MPLS explicit routing, while the WDM NMS relies more on the management plane by implementing routing and wavelength assignment algorithms in the management plane. Another feature of the control plane that will be used in the next version is the protection switching mechanism, although the overall coordination of protection and restoration mechanisms of the different layers will be managed centrally by the INMS.

The proposed system is situated on top of the underlying technology EMSs. The EMSs are capable of interacting with the control plane functional blocks of the network elements for provisioning, reporting, or recovery tasks. These interactions with the control plane are depicted in Fig. 2 by the colored arrows between the IP EMS and the IP control plane (CP), and the WDM EMS and the WDM CP. At the time the first prototype was implemented, only IP/MPLS CP blocks were available. However, the architecture is open to incorporating any new CP components that can replace the management functions; for this reason the WDM CP is also depicted in Fig. 2. When an integrated CP becomes available, which can replace both independent CPs of IP and WDM (the dashed area in Fig. 2), the INMS, with proper adaptation, can directly interact with the integrated CP to request the provisioning of end-to-end LSPs over optical SNC connections. However, even then, direct interactions with the technology-specific NMSs are needed for tasks such as alarm correlation and performance analysis.

The proposed system architecture is foreseen only for one administrative domain. For different administrative domains belonging to different operators, a significant amount of work is needed, since security and network visibility issues between operators should be also addressed. The same is valid when attempting to incorporate other technologies, such as ATM or SDH, as the system becomes more complex.

System Design and Implementation

Since the three NMSs (INMS, IP NMS, and WDM NMS) that had to be designed and implemented present many similarities, a generic architecture was proposed, called the generic NMS framework (G-NMS), and adapted according to the peculiarities of each technology (IP, WDM, INMS). From the fine grain of the G-NMS, the three NMSs were produced. For the purpose of carrying out the functionality of the G-NMS, 15 different components (subsystems) were identified and classified into two categories: application subsystems, which perform management operations relevant to the problem being solved, and supporting subsystems, which perform auxiliary operations needed for smooth operation of the application subsystems. For detailed information about the G-NMS architecture, the reader is referred to [9].

The implementation of the system was done using component-oriented technology. The interfaces of the different subsystems were described using the Common Object Request Broker Architecture (CORBA) Interface Description Language (IDL), whereas for communication between the different components the CORBA bus was used. For the development of the software, two different software development platforms were used. The first is based on the JAVA programming language and uses the CORBA IDL for description of the interfaces; the second uses C++ as the programming language and XML for description of the interfaces. For interworking between the two different management platforms, a gateway was developed that translates the IDL methods to an XML format. The platforms and languages selected are not bound to a specific system architecture, providing the generality and portability of the prototyped system.

The Testbed Environment and Adaptation

The testbed infrastructure for the first prototype release was based on Lucent Technologies' experimental WDM testbed called LAMPION with the add-on of CISCO routers. Figure 3 depicts the testbed environment.

The IP part was composed of three CISCO 7000 series routers as the core routers, and three 1000 or 2000 Cisco routers as the customer edge (CE) routers. The core routers played both the provider (P) and provider edge (PE) roles, according to MPLS Border Gateway Protocol (BGP) terminology, depending on the logical topology chosen for each particular test. The 7000 core routers support MPLS, using Label Distribution Protocol (LDP) for label distribution and RSVP-TE for LSP setup. Moreover, the internal routing protocol is OSPF with traffic engineering extensions. The CE routers ran basic IP capabilities and used default static routes. It should be also mentioned that the data communication network (DCN) used for the flow of management information for the IP routers was a separate LAN based on Ethernet technology; for simplicity reasons it is not depicted in Fig. 3.

The WDM part of the testbed was based on a laboratory testbed. Figure 3 describes a simplified version of it, depicting only three WDM nodes. The distance between two remote nodes is 8 km on average, with a total ring circumference of 24 km. An optical supervisory channel (OSC) at 1310 nm is used to transport the management information of the WDM network.

In order to perform experiments and validate the management system in the testbed environment, an adaptation layer was needed between the southbound interface of the IP and WDM NMSs, and the IP and WDM EMS, respectively. Such an adaptation management system was carried out in order to make the EMSs and NMSs interfaces compatible. The adaptation interface hid the EMS infrastructure and native APIs proprietary to a certain testbed, allowing the technology NMSs to be plugged into different testbeds provided that such an adaptation system is available.

For IP, due to the lack of any suitable open EMS, the adaptation was done directly to the management interface of the network elements (i.e., Simple Network Management Protocol, SNMP, and command line interface, CLI), building from scratch an IP EMS. In our case, the IP elements were commercial products supporting the SNMP protocol. Complementing the SNMP functionality the adaptation procedure used the CLI of the routers and TFTP to upload new configuration files. Since the requested SNMP functionality was not completely incorporated in the elements due to the novelty of the

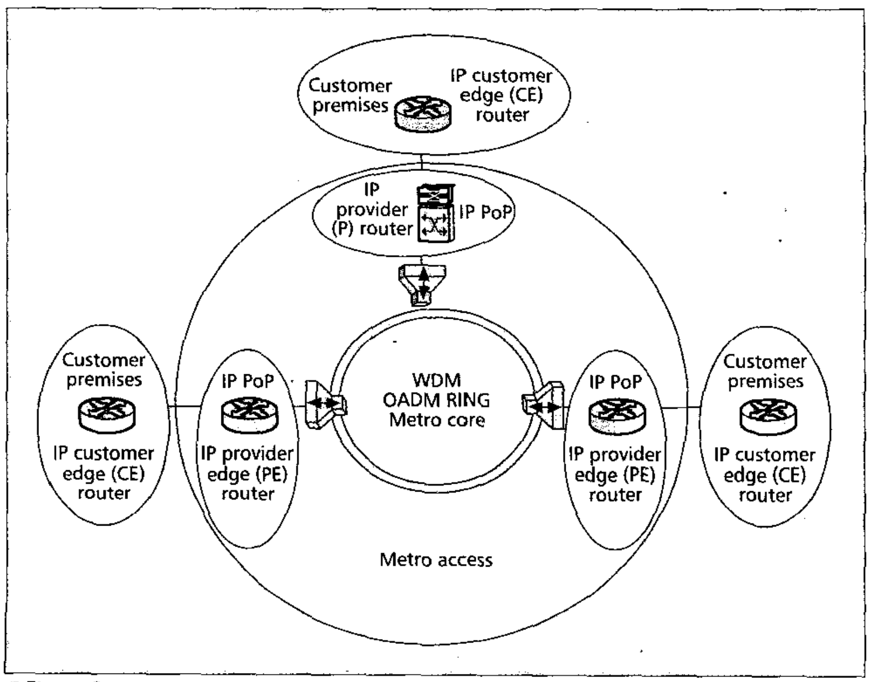
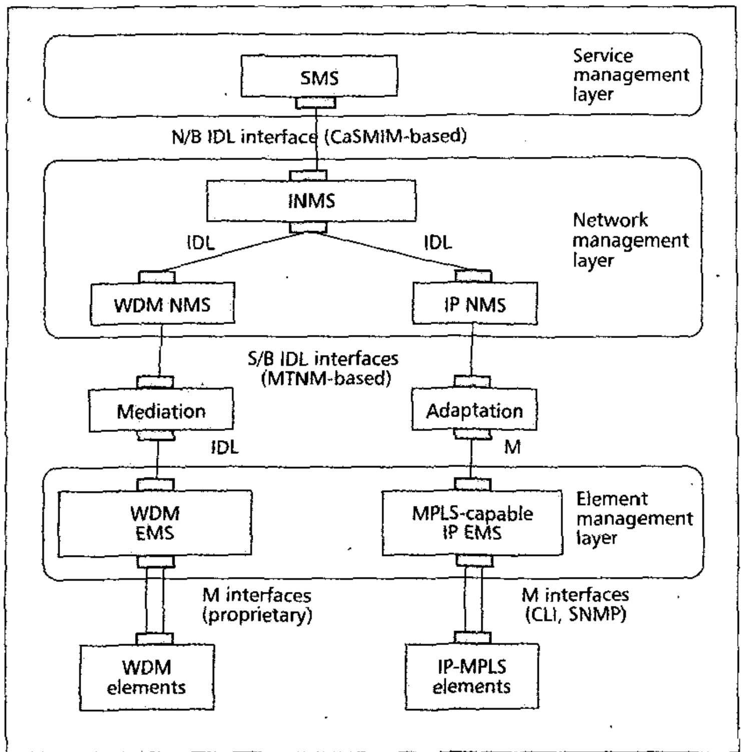


Figure 3. *Testbed environment.*



■ Figure 4. *Interfaces for testbed adaptations.*

relevant management information bases (MIBs) (MPLS-TE, LSR, and LDP), a hybrid solution using SNMP and CLI was used in order to implement the MNTM operations requested from the IP NMS.

On the other hand, the WDM elements were managed via a corresponding EMS that deployed a CORBA IDL interface following the basic profiles of the element layer MTNM interface. Since the WDM elements were made for research purposes in the laboratory, they used a CORBA-based proprietary protocol that was incorporated in the lower part of the WDM EMS. Figure 4 depicts the adaptation layer of both the IP and WDM elements.

System Experiments and Assessment

The INMS developed and in-field integrated was subjected to a series of experiments in the testbed environment described above. By means of these experiments, the management system was verified and evaluated as to what extent it meets the defined requirements and expectations.

The experiments were grouped into two main categories, showing nonfunctional and functional characteristics. The former set of experiments proved that the developed solution has features such as openness, modularity, scalability, and portability. The latter includes experiments that exhibited the basic management functionality of the system, focusing mainly on the integrated or intertechnology functionality and not on single technology functionality. In the current article only the functional characteristics will be discussed, and of them only configuration management. For more information about the scenario used for system evaluation as well as the evaluation of the system itself, the reader should refer to [10].

For the evaluation of the functional attributes related to configuration management, the following experiments have been carried out using the aforementioned testbed:

Network provisioning

- Creation/deletion of an optical path spanning the WDM network
- Creation/deletion of an LSP using the previous optical path
- ICS creation/deletion, where the INMS coordinates the creation of both the LSP and the optical path
- Activation/deactivation of policies influencing the management process

Network inventory

- Network inventory consistency to its infrastructure; that is, auto-discovery of an IP link after an optical path has been established

System Assessment

In general, the proposed system succeeded in carrying out the provisioning of IP path-based connectivity services using MPLS with guaranteed QoS (in terms of guaranteed end-to-end bandwidth) in an automatic and fast way by making the appropriate changes to the IP/MPLS and WDM networks. Traditionally, each layer of IP over WDM is independently managed, having its own requirements, problems, and unique operational characteristics. The proposed system is quite innovative in dealing with the integrated management of those technologies providing fast, differentiated, and reliable IP over WDM connectivity services. Particularly:

- The system was capable of providing multiple LSPs over a nonsaturated optical channel, while an additional optical channel was triggered in case there was insufficient bandwidth to serve the LSP request. However, the provisioning time to create an integrated LSP path over a new optical channel was on the order of minutes (3–4). Such response time is of course unacceptable for commercial management systems; nevertheless, due to the further software development of the system, every possible debugging feature was enabled, resulting in extra latencies of the system.
- The successful interaction between the management systems and CP components was a proof of concept of the proposed synergy approach between the management and control planes, even if there were limited CP components available. The validity of this approach will be further scrutinized in the next release of the management system where an integrated restoration mechanism will be exhibited using both planes.
- The development of the system using two different software platforms, despite the significant interworking problems faced and solved, proved that the proposed architecture is not bound to any particular software platform or programming language. Actually, the component-based nature of the system is one more proof that such a distributed system can actually be used, maximizing the flexibility of the network operator to add and remove "compatible" components on demand, depending on their availability and functionality. Of course, the installation and administration of the system was rather complex compared to existing commercial products.
- Although not covered in detail in the current article, a set of authorization and obligation policies were successfully used in the NMSs, giving more flexibility to the system. The former category of policies supported provisioning tasks, whereas the latter was mainly used to restrict the routing options of the system. The definition of more complex policy rules should be further studied.

Conclusions

This article gives an overview of the design, specification, and implementation of a novel integrated network management system capable of providing IP connectivity services in a hybrid IP over WDM environment. The evaluation and assessment of the proposed management solution is also presented. Although, only the basic configuration management functionality is covered, configuration enhancements dealing with scheduling and enhanced QoS support (delay, jitter, throughput, loss) as well as fault and performance management functionality covering alarm correlation of both technologies, integrated recovery mechanisms, and performance analysis to identify congestion in the network, to mention a few, are currently being implemented, adapted, and tested in OTE's public WDM network, and it is our intention to proceed with an overall assessment of the system.

Acknowledgments

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