PNNI-Based Control Plane for Automatically Switched Optical Networks

Sergio Sánchez-López, Josep Solé-Pareta, Jaume Comellas, John Soldatos, Georgios Kylafas, and Monika Jaeger

***Abstract*—Much effort has been spent on the definition of control plane protocols for automatically switched optical networks (ASON). Most of the proposals brought into the standardization for an International Telecommunications Union—Telecommunication Sector, Internet Engineering Task Force, and Optical Internetworking Forum are based on Internet protocol concepts. One such proposal is the generalized multi-protocol label switching (GMPLS), an extension of the MPLS traffic engineering control plane model that includes nonpacket switched technologies (time, wavelength, and fiber switching). Recently, the potential use of private network-network interface (PNNI) in ASONs has been discussed as an alternative proposal by the standardization bodies. The goal of this paper is to appropriately adapt asynchronous transfer mode into an optical PNNI (O-PNNI) protocol that can be used as the control plane of ASONs. The paper also provides a critical viewpoint on the potential usage of either O-PNNI or GMPLS control plane and analyzes the pros and cons of each. The methodology adopted toward devising O-PNNI hinges on reviewing PNNI along with ASON recommendations in order to determine the set of PNNI features that require adaptation. Having identified these features we engineer and present appropriate solutions relating to routing, signaling and addressing aspects**

***Index Terms*—Automatically switched optical networks (ASONs), control plane, optical networks, private network-network interface (PNNI).**

I. Introduction

THE exponential growth of data traffic is driving the evolution toward optical network infrastructures that enable the provisioning of high-bandwidth optical connections for Internet protocol (IP) centric data, video and voice applications. Although data traffic is growing exponentially, voice traffic, almost stable, is still representing the major source of revenues for network operators; as such to remain competitive. Network operators should be able to provide optical switched transport services while making optimal use of network resources and reducing the network complexity. The introduction of intelligence by means of signaling and routing protocols in optical networks allows meeting emerging requirements such as dynamic and rapid provisioning of connections, automatic topology discovery and network inventory, reactive traffic engineering, and faster optical restoration.

As a result of the standardization effort for optical networking, a first model has been recently approved: the automatically switched optical network (ASON) [1]. While current optical networks only provide transport capacity, the ASON allows to dynamically setup and tear down optical channels. A key issue in order to achieve this functionality is the definition of a control plane, which is responsible for the routing and signaling processes on the ASON.

Much effort has been spent on the definition of control plane protocols for ASONs. Most of the proposals brought into the standardization bodies, the International Telecommunications Union—Telecommunication Sector (ITU-T), Internet Engineering Task Force (IETF), and Optical Internetworking Forum (OIF), are based on IP related concepts. In this way, generalized multiprotocol label switching (GMPLS) protocols, which leverage the MPLS traffic engineering mechanisms for optical networks, are widely accepted as the most appropriate choice to implement the ASON control plane.

However, discussions about the potential use of private network-network interface (PNNI) in ASONs, have started recently in standardization for two main reasons. First, many PNNI features perfectly meet ASON requirements. Second, PNNI is mature and widely distributed in today's transport networks, and it is supported on the equipment of leading vendors (e.g., Cisco, Lucent, Nortel, Alcatel). Thus, PNNI in ASONs allows carriers to take advantage of their experience with PNNI in asynchronous transfer mode (ATM) networks. For example, PNNI is already embedded in the equipment base of optical switch vendors such as Ciena, whose optical switching and routing protocol (OSRP) is based on ATM PNNI [13]. Note that it is not mandatory to use an ATM transport plane together with the PNNI protocol.

PNNI has the potential of becoming a protocol for efficiently supporting ASON control plane since it includes many interesting features such as

— high routing scalability with multiple (up to 104) levels of hierarchy;
— automatic topological and resource discovery;
— support for protection and restoration mechanisms and crankback capabilities;
— call admission control (CAC);

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S. Sánchez-López, J. Solé-Pareta, and J. Comellas are with the Universitat Politècnica de Catalunya (UPC) Advanced Broadband Communications Laboratory (CCABA), 08034 Barcelona, Catalunya, Spain (e-mail: sergio@ac.upc.es; pareta@ac.upc.es; comellas@tsc.upc.es).

J. Soldatos is with Athens Information Technology, GR-19002 Athens, Greece (e-mail: jsol@ait.gr).

G. Kylafas is with the Electrical and Computer Engineering Department, National Technical University of Athens (NTUA), GR-15773 Zografou, Athens, Greece (e-mail: gkyla@telecom.ntua.gr).

M. Jaeger is with the T-Systems ET-161a, 10589 Berlin, Germany (e-mail: Monika.Jaeger@t-systems.com).

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TABLE I
PNNI STANDARD FEATURES AND ASON REQUIREMENTS

Features	PNNI STANDARD	ASON REQUIREMENTS
Scalability	Hierarchical structure Summarisation of topology information	Hierarchical routing Link bundling and link state information classification
Topology discovery	Topology/resource dissemination Neighbours discovery Flooding mechanism	Topology has to be discovered using a dissemination mechanism
Path selection	Connection-oriented Routing algorithm is not specified. Defines a set of features to be carried out by any routing algorithm	Connection-oriented. Computation depends on: available information, computation algorithm and Input requirements
Connection Set-up/tear-down	Supported	Required
Soft permanent connections	Supported	Required
Restoration	Supported	Required
Solution to no suitable resources in the computed path.	Crankback mechanism	Not required but possibly needed
Signalling exchange	In-band	Out-of-band is required.
Addressing	ATM End System Addresses (AESA)	Address scheme necessary

— traffic management functions;
— unidirectional and bi-directional support of permanent virtual connection (PVC), switched virtual connection (SVC), and soft-permanent virtual connection (SPVC);
— resilience functions in case of failures (pre-planned or on-demand); "slow" re-rerouting for optimization purposes (make before brake);
— support for multicasting.

The goal of this paper is to introduce an optical PNNI (O-PNNI) as an adaptation of the ATM-PNNI protocol for optical networks, and to compare O-PNNI with its GMPLS counterparts, by looking at pros and cons of each approach. PNNI is reviewed along with ASON recommendations in order to determine the set of PNNI features that require adaptation for supporting an ASON control plane. Having identified these features we engineer and present the appropriate solutions. This methodology has been followed in two parallel directions: first toward adapting the routing protocol and next toward devising an O-PNNI signaling protocol. Moreover, the problem of addressing in the scope of O-PNNI is outlined and potential solutions are presented.

The remaining of this paper is organized as follows. Section II uses the ASON requirements and the PNNI standard features to point out which PNNI functions require adaptation to become part of the O-PNNI definition. Sections III–V deal with the specification of routing, signaling, and addressing aspects for the O-PNNI. Section VI compares O-PNNI and GMPLS control plane models. Finally, a summary highlighting the main conclusions of this work is given in Section VII.

II. O-PNNI DEFINITION

O-PNNI can be defined as a suite of control protocols for ASTN/ASON networks, which are based on the ATMs Forum PNNI protocol. As a result the core O-PNNI protocols are based on the functions and features of the ATM PNNI [2], along with the ASON Requirements, which are based on ITU-T recommendations [1], [3]. Specifically, O-PNNI includes standard PNNI features fulfilling certain ASON requirements, as well as any necessary PNNI extensions toward fully supporting the features specified within [1], [3]. O-PNNI hinges on the fact that many PNNI standard features are also fulfilling ASON requirements. This is illustrated in Table I, which lists a set of important ASON requirements and the corresponding PNNI features. Note that Table I provides a starting point toward determining the set of PNNI features that require adaptation for supporting an ASON control plane.

O-PNNI can be seen as an alternative control plane to the one provided by GMPLS. Both are based on existing protocols

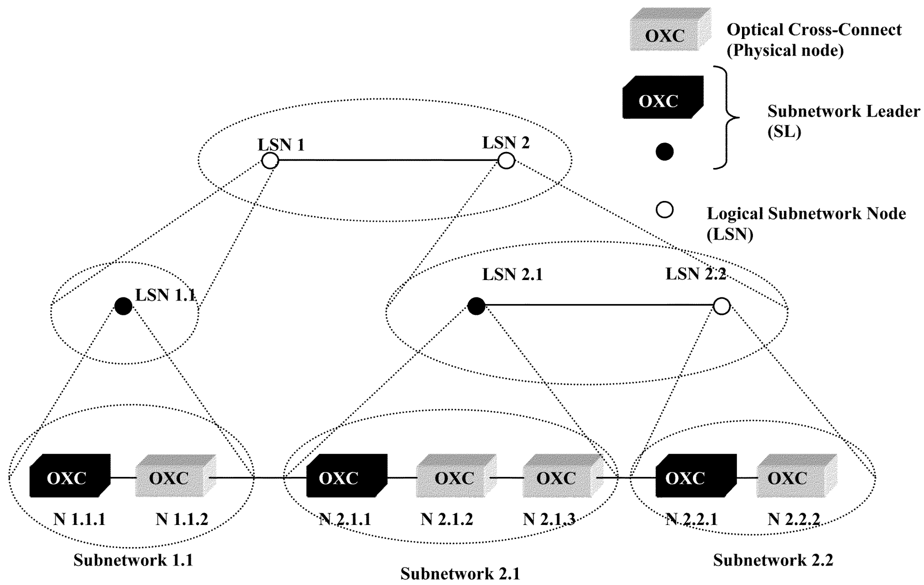

Fig. 1. An O-PNNI/ASON hierarchical structure for routing.

(such as MPLS and PNNI). Having an alternative to Open Shortest Path First/Border Gateway Protocol (OSPF/BGP) routing and Resource Reservation Protocol/Label Distribution Protocol (RSVP/LDP) signaling is by itself a sufficient motivation for studying and developing O-PNNI. In addition, recent experience with GMPLS-based control plane deployments for optical networks is boosting the belief that some issues could be tackled more efficiently by O-PNNI. Some of these issues stem from the fact that packet switched networks (such as MPLS based networks) differ significantly from circuit-switched networks (such as an ASON). Also, PNNI provides a richer set of functionality compared to GMPLS, e.g., PNNIs inherent support for quality of service (QoS)-based routing, while GMPLS relies on traditional OSFP/BGP without QoS capabilities. Furthermore, PNNI can optionally use a generic call admission control (GCAC) algorithm, which is not readily available in GMPLS protocols. This extra functionality is another driver toward working on the evolution of the mature and reliable ATM PNNI, to O-PNNI. Specifying O-PNNI requires the provision of a routing and a signaling protocol that are appropriate for ASON. Since an important issue associated with the use of O-PNNI is that it is more difficult to integrate with IP client networks, it is imperative that a solution for a smooth integration with IP clients is discussed.

There are several standard PNNI features that demand adaptation before being used in the scope of ASON network control. The main areas of these adaptations are: 1) the adaptation of PNNIs hierarchical routing structure to ASON needs; 2) the adaptation of routing information dissemination and path selection mechanisms; and 3) the adaptation of signaling formats, parameters, and mechanisms.

III. O-PNNI Routing Aspects

This section elaborates on source-based hierarchical routing for supporting scalability as well as security in a large network. The main advantage of a hierarchical routing approach is to reduce large routing information overhead and to enable routing scalability. An ASON oriented adaptation of the ATM PNNI routing [2] has to take into account the following aspects: a hierarchical structure of the network, information dissemination and a path selection mechanism.

The PNNI hierarchy can be directly applied to ASONs in order to ensure that the protocol for distributing topology information scales well for worldwide optical networks [4]. We propose an ASON routing structure, which consists of subdividing the network into subnetworks. These subnetworks contain physical nodes with similar features. Subnetwork nodes exchange topology and resource information amongst themselves in order to maintain an identical view of the subnetwork. This information is contained in a routing controller (RC) component, which responds both to requests from connection controllers (CC) for path information needed to set up connections, and to requests for topology information for hierarchy mechanism. Each subnetwork is identified by a subnetwork identifier (SID), which is specified at configuration time. The neighbor nodes exchange these SIDs to discover whether they belong to the same subnetwork. A border node is characterized by at least two different SIDs. A SID may be identified as a prefix of the subnetwork address (IP or ATM end system address).

For each subnetwork there is a "logical subnetwork node" (LSN) representation in the next hierarchical level. The necessary functions to perform this role are executed by a node called "subnetwork leader" (SL). This node receives complete topology state information from all subnetwork nodes and feeds information up to the LSN. The propagated information is the only information needed by the higher level.

An example of the hierarchically configured network is depicted in Fig. 1.

The network information dissemination process of the ATM PNNI routing also can be directly applied to the ASON taking into consideration that the topology and resource information

TABLE II
POTSE INFORMATION

CONTENT	DESCRIPTION
POTSE Identity and capabilities	Selects the SL and sets up the O-PNNI hierarchy.
Inter-domain link resources to select a path	Fulfil the bandwidth requirements requested by the client.
Reachability information	A node informing its neighbours about the reachable clients through itself.
Directionality attributes	Specify if an optical connection is unidirectional or bi-directional.
Traffic Engineering (TE) information.	This constitutes a set of TE attributes through the domains. This information should allow the network resources to be optimally utilised.
Transport service information.	Required to select a path, which will satisfy the client transport service requirement.
Protection capability information.	Required to support QoS functions.
Shared Risk Link Group (SRLG)	Required for end-to-end SRLG disjoint diverse path service.

will be optical information. Therefore, the PNNI topology state element (PTSE) content must be modified in order to contain the required optical information. In this way, a new element called PNNI optical topology state element (POTSE) is introduced.

In order to determine the local state information, each node exchanges HELLO packets with its direct neighbors. This information has to include the node identifier, the neighbor nodes in the same subnetwork and the state of the links with its neighbors. In addition, each node bundles its state information in one or more POTSEs, which are grouped within a PNNI optical topology state packet (POTSP). This packet is disseminated throughout the subnetwork via PNNI flooding mechanism. POTSEs flow horizontally through a subnetwork and downwards into and through lower hierarchical levels.

An SL sends the information up to the LSN, which is needed by the higher level, i.e., a summary of the topology/resource information received by the SL from all the nodes belonging to the same subnetwork. There will be two types of information: reachability and topology aggregation.

- Reachability refers to summarized address information needed to determine which addresses can be reached through the lower level subnetwork. Moreover, it should include the control plane address of the next node in order to allow a domain to set up a connection across that node. Since an optical network connection must be bi-directional, this information should include directionality attributes.
- Topology aggregation will be the process of summarizing the topology information of a lower subnetwork in order to reduce the volume of information advised in the higher level. The summary types will be topology and available resource information.

Optical networks impose some unique routing issues such as large amounts of control information to be managed if link state databases have to maintain per-wavelength information. The proposed source-based hierarchical routing for O-PNNI helps to overcome this problem because its hierarchical approach ensures that the source nodes do not need to maintain large databases with specific information about all nodes and links in the network. Routing advertisements are reduced and the network scalability is improved.

ASON is a network capable of providing global connectivity, i.e., connections are set up over a number of subnetworks operated by different administrators. Since network operators usually do not share topology and resource information, an NNI between two different domains, i.e., an External NNI (E-NNI), exhibits different behaviors than an NNI within a single domain, i.e., internal NNI (I-NNI). According to the topology aggregation concept, O-PNNI could be used as an E-NNI to provide a reduced set of the available features between different domains. This information is only a summary of the topology and available resource information that does not reveal the complete network domain topology.

Based on the OIF NNI routing requirements [5] and the requirements for routing in ASON [15], the proposed POTSE contains the information, as shown in Table II.

PNNI does not specify a routing algorithm in order to *compute routing paths*. However, it defines a set of features, which have to be supported by any routing algorithm running over the PNNI network. In the scope of an O-PNNI path, computation will be performed starting from the source routing concept, in which the routing controller (RC) in the ingress node computes the end-to-end route. The selected path will be either based on a “strict explicit route” or a “loose explicit route.”

- According to the strict explicit route paradigm when the path is computed at the ingress node subnetwork, the ingress node has the complete topology information. As a result, the computed route contains all the path details.
- In the loose explicit route case, the ingress node has abstract network topology information with summary resource information. The computed route is a hierarchical route and is encoded in a designated transit list (DTL). The

path contains all topology details about the ingress node subnetwork, but it will contain a sequence of logical subnetwork nodes as a topology abstraction of the rest of the network.

Therefore, the computation algorithm has to support the following functions:

- diverse path computation including link disjoint, node disjoint and shared risk logical groups (SRLG) disjoint paths for the calculation of backup paths;
- inclusion of a hop list (DTL) in the path computation;
- optimized path computation based on TE metrics;
- connection properties requested by the client, which include bandwidth constraints.

Closely related to the path computation and routing functions are the traffic/QoS control features of PNNI. PNNI provides the necessary information (through PTSE elements) to allow switching nodes to perform CAC. Moreover, PNNI supports a generic CAC function, which indicates whether a PNNI node can admit a new connection. O-PNNI incorporates similar CAC/QoS control functionality. In O-PNNI, a CAC indication can be based on the node's topology database, as well as on the connection's attributes such as its service category, traffic characteristics, and QoS requirements. Having computed a path based on the abovementioned POTSE information and computation algorithms, each network node along the chosen path performs the CAC function (note that the particular CAC is not standardized). The ability of each node to correctly perform CAC hinges on the availability of up to date-link/path-state information. Once an ASON node accepts a connection, its resource availability may change significantly. In such cases, new POTSE instances describing the updated resource availability of the node will be produced and accordingly advertised.

On top of a CAC procedure supported by an ASON node, O-PNNI can also include a *generic CAC* (GCAC) in the scope of the path selection process. GCAC is used to provide an almost safe prediction about a link's or node's resource availability regarding a particular lightpath. Based on this prediction O-PNNI should include (or exclude) a link or node if the ASON node is likely to accept the proposed connection (or not). Practically, a GCAC attempts to predict the outcome of the actual CAC performed at an ASON node. Hence, GCAC constitutes a useful tool toward efficiency in path computation and routing, through minimizing crankbacks. Supporting the GCAC function in the scope of O-PNNI requires that each node advertises a set of topology state parameters carrying information required by the generic CAC.

O-PNNIs inherent and mature support for CAC, as well as the ability to support a GCAC function constitutes one of its clear advantages over GMPLS.

IV. O-PNNI SIGNALLING ASPECTS

Signaling is another key aspect of O-PNNI. A thorough study of the ITU-T recommendations for ASON, along with PNNI features outlined in the relevant ATM Forum's documents [2], reveals that PNNI protocols and their operation fulfil most of ASONs signaling requirements. It is worth noting that intensive work is currently carried out both within the ITU-T and the ATM Forum, toward basing signaling operation in PNNI (see, for example, [6], [7]). In particular, work within recommendation [6] is in an early stage toward the adaptation of conventional PNNI signaling messages, in terms of: 1) functional definition and content; 2) format and element coding; and 3) call/connection control procedures.

In this paper, we outline recommended ASON features and mechanisms that are not directly supported by PNNI. This set of features demands that PNNI signaling be accordingly adapted, so that the resulting O-PNNI signaling complies with the full suite of ASON requirements. Some PNNI features requiring adaptation are also identified in [8].

PNNI signaling adaptation for ASON requires the support of the following requirements.

Support of out-of-band signaling MPLS performs in-band signaling, i.e., it uses the data channel to transport signaling messages. In this way, there is an implicit association of a control channel to a data channel. A different case is when there is no explicit association of control channels to data channels, as in GMPLS, which supports separated control and data planes. In this case, additional signaling information is needed to identify the particular data channel. This feature is important to support technologies where the control traffic cannot be sent in-band with the data traffic. GMPLS supports explicit data channel identification by providing interface identification information. The upstream node indicates the selected data interface using suitable addresses and identifiers [9]. As MPLS, PNNI uses in-band signaling where the signaling information is distinguished from the data traffic by using the Virtual Path Identifiers/Virtual Circuit Identifiers (VPIs/VCIs) with values 5 and 0, respectively. Because separated control and data planes for ASON are recommended, we suggest providing interface identification information to the O-PNNI signaling in order to support an association between both planes. Our suggestion is based on the recommendation G.7713.1 [8], which provides the protocol specifications for the distributed call and connection management based on PNNI/Q2931. We consider two possible options.

— A first option consists of adding a new information element in the signaling messages, which we name interface identifier. This element should include an interface identifier and a node identifier used by the source node to identify a data channel.

— A second option uses a generic identifier transport element, which is defined in the recommendation Q.2931 0. This element is used to carry identifiers between two users. The network may process and examine the contents of this element. Depending on the identifier type, its purpose and structure are defined in the Q.2931 specification. The number of instances of this information element in a message is limited to three. Therefore, we suggest carrying the interface information (related with the data channel) in the generic identifier transport element. Moreover, we suggest adding two instances: an interface identifier and a node identifier for distinguishing between the data control and the transport channels. The format of this element is shown in Fig. 2.

Information Element Identifier = Generic Transport IE (0x7F)		
Ext	Coding Standard	IE instruction Field
Length of contents of information		
Identifier related standard/application		
Identifier type = session (0x01)		
Identifier length = N octets		
Node Identifier (Node address)		
Identifier type = session (0x01)		
Identifier length = M octets		
Interface Identifier		

Fig. 2. Generic identifier transport element.

Support for all types of transport layer networks. PNNI is dedicated to supporting ATM connections, and deals with parameters at the ATM layer. On the other hand O-PNNI constitutes a control plane for optical networks that should be independent of the optical transport layer (e.g., synchronous digital hierarchy (SDH), optical transport network (OTN), and plesiochronous digital hierarchy (PDH)). Note also that according to [1], ASON may be applied to layered networks. In order to support all transport layer types, O-PNNI signaling messages should encompass information declaring the transport layer. Such information must be carried in the setup message to allow call and connection controllers to become aware of the transport layer of the target connection. Given that parameters at the ATM layer are not the sole option, it is imperative that the ATM traffic descriptor field of the PNNI SETUP message is appropriately altered so as to encode the target transport layer type and its associated parameters. The ATM forum is currently working on PNNI extensions to support transport networks other than ATM (i.e., SDH, OTN) [7].

End-to-end message acknowledgment. The flow of PNNI signaling messages from the calling party to the called one and vice versa is perfectly aligned with ASON requirements, except that it does not support end-to-end acknowledgment of SETUP and CONNECT messages. An ASON recommends that Call Controllers cater for end-to-end acknowledgment of these messages, and ensure by this a robust and reliable control plane. Since PNNI signaling messages do not include a CONNECT_ACKNOWLEDGE and a SETUP_ACKNOWLEDGE message, two new messages should be included in the O-PNNI signaling. These messages are shown in Table III.

The format of the acknowledge messages can be derived from the CONNECT_ACKNOWLEDGE message specified in Q.2931 signaling, with an appropriate message type. Note however that due to the global significance of these messages it is essential that they contain the Endpoint reference so that the message can reach its final destination. Based on a 7-byte Endpoint information element we can directly specify the variable part of the CONNECT ACKNOWLEDGE message.

We suggest that the CONNECT_ACKNOWLEDGE message with local significance specified in the scope of Q.2931 is also used in the O-PNNI control plane, since hop-by-hop acknowledgment are extremely valuable when carrying out time critical restoration tasks.

Alarm suppression during connection release ITUs recommendation for ASON [1] suggests distinguishing between changes in the state of connections due to management or control plane actions and changes from network failures. Moreover, it is recommended that alarms regarding these states are appropriately generated and/or suppressed. GMPLS signaling (based on RSVP-TE) tackles this set of requirements through appropriate handling of Administrative Status Information [9]. On the other hand, PNNI does not include an obvious mechanism for suppressing alarms during connection release. A possible solution is to make use of the NOTIFY message that is present in the PNNI signaling. NOTIFY messages are used to convey information with respect to the call or connection. The introduction of a new Notification indicator code, signifying the suppression of all alarms for a given call/connection could provide alarm suppression.

Support all UNI, E-NNI, and I-NNI attributes UNI, E-NNI, and I-NNI SETUP messages contain many attributes. All of these can be directly encapsulated in the scope of PNNI SETUP message. Special provisions should be made to encode appropriately the CoS/GoS fields, and match them with respective parameters contained in the QoS parameters placeholder. In the *adaptation of UNI, E-NNI, and I-NNI signaling messages*, the contents of UNI, E-NNI, and I-NNI signaling messages should be appropriately encapsulated in PNNI signaling messages. PNNI messages provide placeholders for all attributes of these messages, except for the CallSetupConfirm message, as the latter is specified in all three interfaces (UNI, E-NNI, I-NNI). Following the process of defining additional acknowledge we could define SETUP_CONFIRM messages. Apart from the above adaptations and enhancements of PNNI signaling, O-PNNI demands that all return codes and messages recommended by ITU-T for ASON are supported. Work on these enhancements and adaptations is already in progress in the scope of the ITU-T [6].

A. Integrating Client Networks With O-PNNI Signaling

In a pragmatic consideration of an ASON, most client networks are IP based and convey their requirements for switched connections from the RSVP protocol. Signaling interworking is strongly dependent on the routing models and protocols. In general, we assume a signalled overlay model, since the O-PNNI network is likely to be totally decoupled from the different client networks. The use of a peer-to-peer model for interworking between IP client networks and ASON would require a tremendous and unjustified signaling adaptation overhead. Based on these assumptions, we discuss the issues of signaling interworking at the ASON UNI, considering ATM, SDH/SONET, and IP client networks.

- *ATM client networks*. In the case of ATM networks the interworking between ATM signaling and O-PNNI is straightforward. This is because O-PNNI signaling

TABLE III
END-TO-END ACKNOWLEDGE O-PNNI MESSAGES

Message	Direction(*)	Significance	Purpose
CONNECT ACKNOWLEDGE	P→S	Global	Indicates that the calling party has received the called party CONNECT message (i.e. the connection has been established and calling party is in the Active state (NN10))
SETUP ACKNOWLEDGE	S→P	Global	Indicates that called party has received the call/connection request and has therefore entered the Call Initiated phase (NN1) (i.e. called party has not responded to the request yet)

(*) S: Succeeding Party, P: Proceeding Party

messages are derived from Q.2931 signaling. As a result, when an ATM signaling message (e.g., a SETUP message) arrives at the boundary between the client network and the ASON core, the parameters can be directly mapped to the corresponding O-PNNI SETUP message.

- *MPLS/GMPLS/IP client networks*. This interworking case is much more interesting, since RSVP-TE messages have a totally different structure from O-PNNI messages. In this case, a special internetworking signaling unit (IWU) is required to perform the necessary mapping between UNI and NNI signaling protocols. From an implementation perspective this unit can be either attached (i.e., software modules in an attached workstation) or embedded to the border O-PNNI capable OXC node (Fig. 3).
- *SDH/SONET client networks*. Since these clients constitute optical networks, signaling interworking can be rather straightforward based on mapping parameters according to relevant specifications (e.g., ITU-T G.872 [14]). The complexity of such a mapping, however, depends on the transport technology of the backbone network. The mapping will be greatly facilitated by the work on PNNI adaptation for transport networks (including SDH/SONET) [7], which is still in progress.

The IETF has conducted considerable work related to RSVP and ATM signaling interworking. We suggest that this work is reused for the definition of the target signaling interworking, i.e., to map objects in RSVP Path/Resv messages to PNNI signaling parameters. Information about the addresses of the ingress and egress OXCs could be derived from the routing protocols. Also a mapping between GMPLS signaling parameters pertaining to optical networking and the corresponding O-PNNI parameters could be defined. A crucial component of such a mapping is the correspondence of O-PNNI QoS parameters to GMPLS CoS, performed either by the IWU (Fig. 3), or by bandwidth broker software entities residing at the interworking domains.

The IETF provides a framework for the RSVP signaling over ATM [11], [12]. Concepts within this IETF contribution are also applicable in the currently studied interworking, and can be taken into account for tackling with key issues. Nevertheless, it is emphasised that RSVP is purely flow based, whereas GMPLS (i.e., RSVP-TE) and O-PNNI messages consider aggregated flows. Therefore, although there is a framework for adapting RSVP to ATM signaling, there is still a need for the

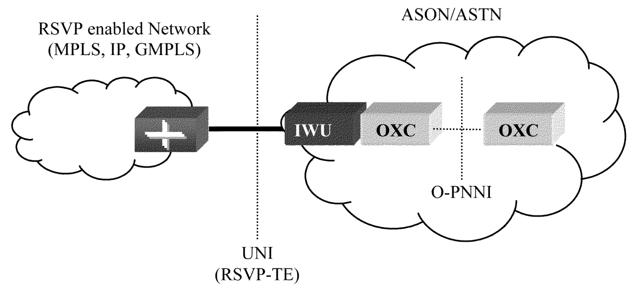

Fig. 3. Network model for RSVP-TE/O-PNNI signaling interworking.

mapping of aggregated RSVP flows to ATM signaling channels. As a result, another important issue is the management of switched lightpaths, which is crucial, given the fact that there are many options regarding the establishment of O-PNNI lightpaths as a result of RSVP signaling messages. Moreover, it is also crucial to provide schemes for mapping RSVP data flows to lightpaths.

V. O-PNNI ADDRESSING ASPECTS

O-PNNI addressing refers to the identification of O-PNNI nodes, for the purpose of performing the routing functions, and establishing and releasing lightpaths. Moreover, a way must be provided for the IP layer to communicate across optical domains. This involves the task of resolving higher layer address endpoints. Although there are potentially several ways to tackle the addressing problem it is always preferable to use existing addressing schemes since they are robust and mature. Also, in most cases existing addressing schemes facilitate the reuse of conventional routing and signaling protocols. O-PNNI protocols are based on traditional ATM/PNNI and therefore do not dispense with IP addresses. Using conventional IP addressing in the scope of O-PNNI is not an obvious choice given the fact that PNNI relies on network service access point (NSAP) addressing for identifying nodes. In the light of these observations we propose three candidate solutions for the addressing problem.

- Use a simple flat nonhierarchical addressing: This is the simplest scheme and is based on administratively assigning unique addresses to all nodes. Such a scheme may be feasible in current optical networks that have

TABLE IV
SUMMARY OF GMPLS AND O-PNNI FEATURES

NNI Functionality	O-PNNI	GMPLS	Comments
Topology discovery & topology information distribution	Yes	Yes	GMPLS supports separate control and transport planes topology. O-PNNI achieves scalability for large world-wide optical networks
Path selection	Yes	Yes	GMPLS: based on OSPF O-PNNI: based on source routing
Signalling exchange	Yes	Yes	O-PNNI and GMPLS: in or out-of-band
Signalling protocol	Yes	Yes	GMPLS: RSVP-TE ("Soft-state" protocol) and CR-LDP ("Hard-state" protocol). O-PNNI: based on Q.2931. "Hard-state" protocol
Multi-layering	Yes	Maybe	O-PNNI explicitly allows 105 levels GMPLS may support it via nested LSPs.
Connection Admission Control	Yes	No	O-PNNI: GCAC and CAC.
Load balancing	Yes	Yes	Both support traffic engineering
Service discovery	No	No	Supported by OIF UNI 1.0 only
Addressing	Yes	Yes	GMPLS: IPv4 and/or IPv6 addresses O-PNNI: NSAP addresses

fairly few nodes. Nevertheless, it does not scale for large optical networks. Also, it does not take advantage of the hierarchical routing capabilities offered in the scope of O-PNNI.

- Adapting the NSAP addresses so that conventional IP addressing can be used: this scheme allows for the smoother integration with client IP based networks. IP addresses can be supported by PNNI by setting the address family identifier (AFI) to a value of 35, thus indicating that IP addresses are used.
- Use of the ATM E.164 addresses, as in original PNNI. Although this option exploits perfectly the hierarchical routing mechanisms of PNNI, it is less easy to integrate with IP client networks. In practice a small subset of E.164 addressing space could be sufficient for supporting ASON node addressing.

VI. O-PNNI OR GMPLS?

O-PNNI constitutes a promising control plane model for implementation in the scope of ASON. However, the industry is currently oriented toward GMPLS based implementations. The project LION (IST-1999-111 387) has selected GMPLS based control plane protocols for implementation in its leading edge ASON testbed. In order to boost O-PNNI implementations, it is essential to know how O-PNNI control planes compare to GMPLS ones.

It has been shown that both GMPLS and O-PNNI are in principle well suited for ASON control planes. There are a lot of technical pros and cons for both frameworks, which are summarized in Table IV. It is a fact that both GMPLS and O-PNNI need further extensions and adaptations, because neither control platform supports all functions identified in this document. Given the industrial momentum of GMPLS, the future of O-PNNI depends on its ability to provide better support for essential control plane features for ASON networks. O-PNNI can provide better support for traffic control and traffic engineering functionality. Moreover, O-PNNI allows for better routing scalability. Observe also that the existence of many stable and mature PNNI implementations can facilitate (i.e., through software reuse) the rapid adoption of O-PNNI in transport network other than ATM. This is extremely useful in the early stages of the market, since it allows vendors and carriers to speed up ASON deployment.

On the O-PNNI downside, GMPLS implementations integrate much better with IP client networks. Also, OPNNI presents a set of potential limitations that are preventing its wide adoption by vendor communities. First, it is ATM-centric, which is often thought to be a "legacy" system on its way out. Second, the primary PNNI addressing scheme is E.164-based, which necessitates translation at any IP border. Also, there are concerns about scaling PNNI, because it is a hierarchical architecture in which the domains, both routing and signaling, are broken into layers. Layered architectures tend to add complexity, which is usually expressed as a set of software problems in interpretation and design.

It must be also emphasized that apart from technical features and requirements, the adoption of either GMPLS or O-PNNI is in all cases political and market driven. Vendors may not want to develop two control planes in parallel and will try to reuse existing software. Operators will decide on technical features but will opt for the solution, which allows easier migration with their existing infrastructure and is more suitable for their existing management systems and network operation staff. Based on these remarks, an operator's choice regarding O-PNNI or GMPLS depends also on its existing investment and infrastructures. For example, O-PNNI will be more appropriate for deployment by incumbent operators that operate legacy ATM backbones featuring PNNI support.

On the other hand, as MPLS finds its way into operators' IP platforms, GMPLS appears as the most appropriate choice for controlling future ASON. In all cases, operators will have to make a selection given that having two different protocol families in one transport network would result in unnecessarily high management complexity and overhead.

VII. Conclusion

This paper has elaborated on general technical guidelines for adopting PNNI for the ASON control plane implementation. This adoption, resulting in O-PNNI, demands that several PNNI features are adapted toward fulfilling ASON control plane requirements. Routing and signaling modifications, needed to adapt PNNI to the ASON requirements, have been proposed. The proposed modifications are recommended in addition to on-going work in the ITU-T and the ATM forum toward PNNI signaling adoption in optical transport networks. Overall, the feasibility of O-PNNI as ASON control plane has been demonstrated. O-PNNI, as a mature technology, could be very practical for a seamless migration from current transport networks to ASON. The adoption of the GMPLS or O-PNNI approach might be influenced by several factors, not least the expected high penetration of IP and its integration with optics. Using GMPLS or O-PNNI as an ASON/ASTN control plane is a choice that needs to consider a host of tradeoff factors. The most important of these have been highlighted in the section comparing the two alternatives.

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Sergio Sánchez-López received the B.S. degree in telecommunication engineering from the Polytechnic University of Catalonia, Barcelona, Spain, in 1989, the M.S. degree in electrical engineering from the University of Barcelona, Barcelona, Spain, in 1996, and the Ph.D. degree in telecommunications engineering from the Polytechnic University of Catalonia in 2003.

He has been an Associate Professor in the Computer Architecture Department at Polytechnic University of Catalonia since 1992. His research interests include asynchronous transfer mode, multiprotocol label switching, and optical networks. He has been involved in the IST project LION.

Josep Solé-Pareta received the M.S. degree in telecommunication engineering and the Ph.D. degree in computer science from the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, in 1984 and 1991, respectively.

In 1984, he joined the Computer Architecture Department of UPC. Since 1992, he has been an Associate Professor with this department. He is Co-Founder and Member of the Advanced Broadband Communications Centre of UPC (http://www.ccaba.upc.es). His current research interests are in broad-band Internet and high-speed and optical networks.

Jaume Comellas was born in Badalona, Spain, in 1965. He received the M.S. and Ph.D. degrees in telecommunications engineering from the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, in 1993 and 1999, respectively.

Since 1992, he has been a Staff Member of the Optical Communications Research Group of UPC and is an Assistant Professor in the Signal Theory and Communications Department of UPC. His current research interests mainly concern optical transmission and networking topics. He has participated in various research projects fund by the Spanish Government and the European Commission.

John Soldatos received the B.S. and M.Sc. degrees from the Electrical and Computer Engineering Department, National Technical University of Athens, Athens, Greece, in 1996 and the Ph.D. degree from the Electrical and Computer Engineering Department, National Technical University of Athens, in 2000.

He has had an active role in a number of ACTS, ESPRIT and IST research projects (EXPERT AC-094, WATT AC-235, IMPACT AC-324, Chameleon EP 20597, CATCH-2004 IST-1999-11103, and LION IST-19990-11387). He also has extensive experience in the technical managment of industrial IT projects, where he has collaborated with leading enterprises in Greece (INTRACOM S.A, IBM Hellas S.A, INFO-QUEST S.A, OTE, TEMAGON S.A). Since March 2003, he has been with Athens Information Technology, Athens, Greece. As a result of his activities, he has published more than 25 papers in international journals and conference proceedings. His current research interests include IPv6, intelligent high-capacity optical networks, grid networking, and networking for multimodal applications.

Georgios Kylafas received the degree from the Electrical and Computer Engineering Department of the National Technical University of Athens (NTUA), Athens, Greece, in 2001. He is currently working toward the Ph.D. degree with the Telecommunications Laboratory of the Electrical and Computer Engineering Department, NTUA.

He has actively participated in the European IST LION project, where he was mainly involved in optical resilience and simulation. His research interests include network resilience, network simulation, and Internet protocols.

Monika Jaeger received the degree in electrical engineering from Munich University of Technology, Munich, Germany, in 1992.

She held previous positions with the Fraunhofer Institute for Open Communication Systems, Berlin, Germany from 1995 to 1998 and DeTeWe, Berlin, Germany, from 1992 to 1995. Since 1998, she has been a Senior Research Engineer in the Department of Photonic Networks and Network Architecture at T-Systems, Technologiezentrum, Berlin, Germany. Her current research interests are in the area of optical transport network design. She has been involved in the IST project LION.