          Framework for Generalized Multi-Protocol Label
        Switching (GMPLS)-based Control of Synchronous Digital
     Hierarchy/Synchronous Optical Networking (SDH/SONET) Networks

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Abstract

   Generalized Multi-Protocol Label Switching (GMPLS) is a suite of
   protocol extensions to MPLS to make it generally applicable, to
   include, for example, control of non packet-based switching, and
   particularly, optical switching. One consideration is to use GMPLS
   protocols to upgrade the control plane of optical transport networks.
   This document illustrates this process by describing those extensions
   to GMPLS protocols that are aimed at controlling Synchronous Digital
   Hierarchy (SDH) or Synchronous Optical Networking (SONET) networks.
   SDH/SONET networks make good examples of this process for a variety
   of reasons. This document highlights extensions to GMPLS-related
   routing protocols to disseminate information needed in transport path
   computation and network operations, together with (G)MPLS protocol
   extensions required for the provisioning of transport circuits. New
   capabilities that an GMPLS control plane would bring to SDH/SONET
   networks, such as new restoration methods and multi-layer circuit
   establishment, are also discussed.

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1. Introduction

   The CCAMP Working Group of the IETF has the goal of extending MPLS
   [1] protocols to support multiple network layers and new services.
   This extended MPLS, which was initially known as Multi-Protocol
   Lambda Switching, is now better referred to as Generalized MPLS (or
   GMPLS).

   The GMPLS effort is, in effect, extending IP/MPLS technology to
   control and manage lower layers. Using the same framework and
   similar signaling and routing protocols to control multiple layers
   can not only reduce the overall complexity of designing, deploying,
   and maintaining networks, but can also make it possible to operate
   two contiguous layers by using either an overlay model, a peer model,
   or an integrated model. The benefits of using a peer or an overlay
   model between the IP layer and its underlying layer(s) will have to
   be clarified and evaluated in the future. In the mean time, GMPLS
   could be used for controlling each layer independently.

   The goal of this work is to highlight how GMPLS could be used to
   dynamically establish, maintain, and tear down SDH/SONET circuits.
   The objective of using these extended IP/MPLS protocols is to provide
   at least the same kinds of SDH/SONET services as are provided today,
   but using signaling instead of provisioning via centralized
   management to establish those services. This will allow operators to
   propose new services, and will allow clients to create SDH/SONET
   paths on-demand, in real-time, through the provider network. We
   first review the essential properties of SDH/SONET networks and their
   operations, and we show how the label concept in GMPLS can be
   extended to the SDH/SONET case. We then look at important
   information to be disseminated by a link state routing protocol and
   look at the important signal attributes that need to be conveyed by a
   label distribution protocol. Finally, we look at some outstanding
   issues and future possibilities.

1.1. MPLS Overview

   A major advantage of the MPLS architecture [1] for use as a general
   network control plane is its clear separation between the forwarding
   (or data) plane, the signaling (or connection control) plane, and the
   routing (or topology discovery/resource status) plane. This allows
   the work on MPLS extensions to focus on the forwarding and signaling
   planes, while allowing well-known IP routing protocols to be reused
   in the routing plane. This clear separation also allows for MPLS to
   be used to control networks that do not have a packet-based
   forwarding plane.

An MPLS network consists of MPLS nodes called Label Switch Routers
(LSRs) connected via Label Switched Paths (LSPs). An LSP is uni-
directional and could be of several different types such as point-
to-point, point-to-multipoint, and multipoint-to-point. Border LSRs
in an MPLS network act as either ingress or egress LSRs, depending on
the direction of the traffic being forwarded.

Each LSP is associated with a Forwarding Equivalence Class (FEC),
which may be thought of as a set of packets that receive identical
forwarding treatment at an LSR. The simplest example of an FEC might
be the set of destination addresses lying in a given address range.
All packets that have a destination address lying within this address
range are forwarded identically at each LSR configured with that FEC.

To establish an LSP, a signaling protocol (or label distribution
protocol) such as LDP or RSVP-TE is required. Between two adjacent
LSRs, an LSP is locally identified by a fixed length identifier
called a label, which is only significant between those two LSRs. A
signaling protocol is used for inter-node communication to assign and
maintain these labels.

When a packet enters an MPLS-based packet network, it is classified
according to its FEC and, possibly, additional rules, which together
determine the LSP along which the packet must be sent. For this
purpose, the ingress LSR attaches an appropriate label to the packet,
and forwards the packet to the next hop. The label may be attached
to a packet in different ways. For example, it may be in the form of
a header encapsulating the packet (the "shim" header) or it may be
written in the VPI/VCI field (or DLCI field) of the layer 2
encapsulation of the packet. In case of SDH/SONET networks, we will
see that a label is simply associated with a segment of a circuit,
and is mainly used in the signaling plane to identify this segment
(e.g., a time-slot) between two adjacent nodes.

When a packet reaches a packet LSR, this LSR uses the label as an
index into a forwarding table to determine the next hop and the
corresponding outgoing label (and, possibly, the QoS treatment to be
given to the packet), writes the new label into the packet, and
forwards the packet to the next hop. When the packet reaches the
egress LSR, the label is removed and the packet is forwarded using
appropriate forwarding, such as normal IP forwarding. We will see
that for an SDH/SONET network these operations do not occur in quite
the same way.

1.2. SDH/SONET Overview

   There are currently two different multiplexing technologies in use in
   optical networks: wavelength-division multiplexing (WDM) and time
   division multiplexing (TDM). This work focuses on TDM technology.

   SDH and SONET are two TDM standards widely used by operators to
   transport and multiplex different tributary signals over optical
   links, thus creating a multiplexing structure, which we call the
   SDH/SONET multiplex.

   ITU-T (G.707) [2] includes both the European Telecommunications
   Standards Institute (ETSI) SDH hierarchy and the USA ANSI SONET
   hierarchy [3]. The ETSI SDH and SONET standards regarding frame
   structures and higher-order multiplexing are the same. There are
   some regional differences in terminology, on the use of some overhead
   bytes, and lower-order multiplexing. Interworking between the two
   lower-order hierarchies is possible using gateways.

   The fundamental signal in SDH is the STM-1 that operates at a rate of
   about 155 Mbps, while the fundamental signal in SONET is the STS-1
   that operates at a rate of about 51 Mbps. These two signals are made
   of contiguous frames that consist of transport overhead (header) and
   payload. To solve synchronization issues, the actual data is not
   transported directly in the payload, but rather in another internal
   frame that is allowed to float over two successive SDH/SONET
   payloads. This internal frame is named a Virtual Container (VC) in
   SDH and a SONET Payload Envelope (SPE) in SONET.

   The SDH/SONET architecture identifies three different layers, each of
   which corresponds to one level of communication between SDH/SONET
   equipment. These are, starting with the lowest, the regenerator
   section/section layer, the multiplex section/line layer, and (at the
   top) the path layer. Each of these layers, in turn, has its own
   overhead (header). The transport overhead of an SDH/SONET frame is
   mainly sub-divided in two parts that contain the regenerator
   section/section overhead and the multiplex section/line overhead. In
   addition, a pointer (in the form of the H1, H2, and H3 bytes)
   indicates the beginning of the VC/SPE in the payload of the overall
   STM/STS frame.

   The VC/SPE itself is made up of a header (the path overhead) and a
   payload. This payload can be further subdivided into sub-elements
   (signals) in a fairly complex way. In the case of SDH, the STM-1
   frame may contain either one VC-4 or three multiplexed VC-3s. The
   SONET multiplex is a pure tree, while the SDH multiplex is not a pure
   tree, since it contains a node that can be attached to two parent

nodes. The structure of the SDH/SONET multiplex is shown in Figure
1. In addition, we show reference points in this figure that are
explained in later sections.

The leaves of these multiplex structures are time slots (positions)
of different sizes that can contain tributary signals. These
tributary signals (e.g., E1, E3, etc) are mapped into the leaves
using standardized mapping rules. In general, a tributary signal
does not fill a time slot completely, and the mapping rules define
precisely how to fill it.

What is important for the GMPLS-based control of SDH/SONET circuits
is to identify the elements that can be switched from an input
multiplex on one interface to an output multiplex on another
interface. The only elements that can be switched are those that can
be re-aligned via a pointer, i.e., a VC-x in the case of SDH and a
SPE in the case of SONET.

```
           xN          x1
STM-N<----AUG<----AU-4<--VC4<----------------------------C-4  E4
          ^             ^
          Ix3           Ix3
          I             I           x1
          I             -----TUG-3<----TU-3<---VC-3<---I
          I                       ^                        C-3 DS3/E3
STM-0<------------AU-3<---VC-3<-- I -------------------I
                          ^       I
                          Ix7     Ix7
                          I       I    x1
                          -----TUG-2<---TU-2<---VC-2<---C-2 DS2/T2
                             ^  ^
                             I  I   x3
                             I  I----TU-12<---VC-12<--C-12 E1
                             I
                             I        x4
                             I-------TU-11<---VC-11<--C-11 DS1/T1
```

```
              xN
    STS-N<------------------SPE<----------------------------DS3/T3
                            ^
                            Ix7
                            I               x1
                            I---VT-Group<---VT-6<----SPE DS2/T2
                                ^  ^  ^
                                I  I  I  x2
                                I  I  I-----VT-3<----SPE DS1C
                                I  I
                                I  I     x3
                                I  I--------VT-2<----SPE E1
                                I
                                I         x4
                                I-----------VT-1.5<--SPE DS1/T1
```
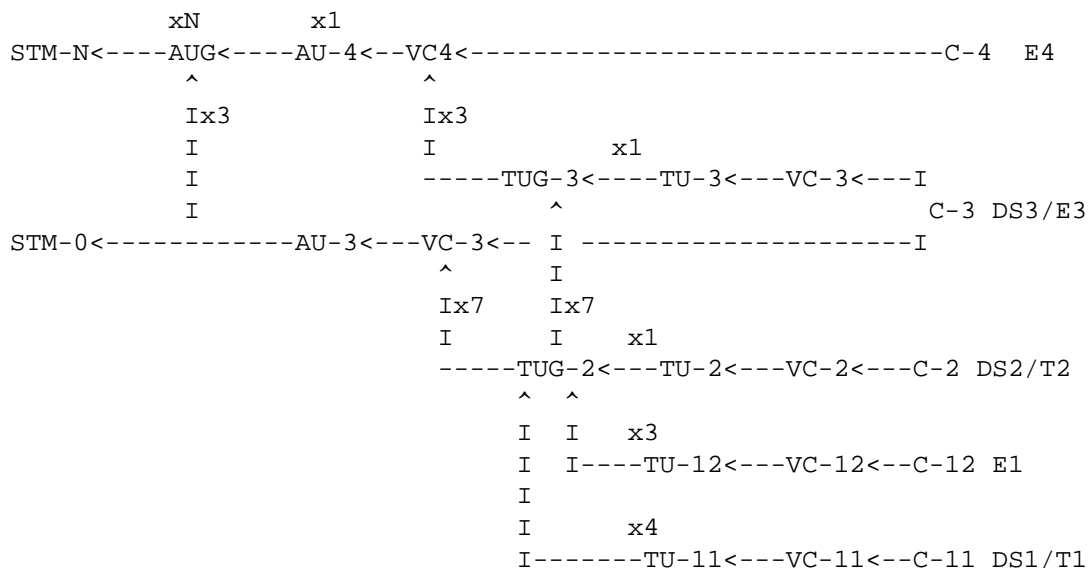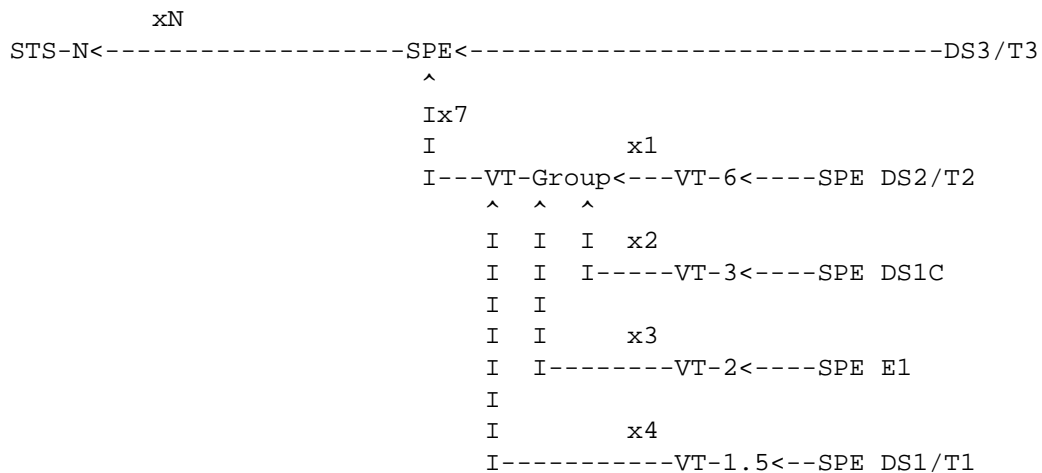
Figure 1. SDH and SONET multiplexing structure and typical
Plesiochronous Digital Hierarchy (PDH) payload signals.

An STM-N/STS-N signal is formed from N x STM-1/STS-1 signals via byte
interleaving. The VCs/SPEs in the N interleaved frames are
independent and float according to their own clocking. To transport
tributary signals in excess of the basic STM-1/STS-1 signal rates,
the VCs/SPEs can be concatenated, i.e., glued together. In this
case, their relationship with respect to each other is fixed in time;
hence, this relieves, when possible, an end system of any inverse
multiplexing bonding processes. Different types of concatenations
are defined in SDH/SONET.

For example, standard SONET concatenation allows the concatenation of
M x STS-1 signals within an STS-N signal with M <= N, and M = 3, 12,
48, 192, ... The SPEs of these M x STS-1s can be concatenated to
form an STS-Mc. The STS-Mc notation is short hand for describing an
STS-M signal whose SPEs have been concatenated.

1.3. The Current State of Circuit Establishment in SDH/SONET Networks

In present day SDH and SONET networks, the networks are primarily
statically configured. When a client of an operator requests a
point-to-point circuit, the request sets in motion a process that can
last for several weeks or more. This process is composed of a chain
of shorter administrative and technical tasks, some of which can be
fully automated, resulting in significant improvements in
provisioning time and in operational savings. In the best case, the
entire process can be fully automated allowing, for example, customer
premise equipment (CPE) to contact an SDH/SONET switch to request a
circuit. Currently, the provisioning process involves the following
tasks.

1.3.1. Administrative Tasks

   The administrative tasks represent a significant part of the
   provisioning time. Most of them can be automated using IT
   applications, e.g., a client still has to fill a form to request a
   circuit. This form can be filled via a Web-based application and can
   be automatically processed by the operator. A further enhancement is
   to allow the client's equipment to coordinate with the operator's
   network directly and request the desired circuit. This could be
   achieved through a signaling protocol at the interface between the
   client equipment and an operator switch, i.e., at the UNI, where
   GMPLS signaling [4], [5] can be used.

1.3.2. Manual Operations

   Another significant part of the time may be consumed by manual
   operations that involve installing the right interface in the CPE and
   installing the right cable or fiber between the CPE and the operator
   switch. This time can be especially significant when a client is in
   a different time zone than the operator's main office. This first-
   time connection time is frequently accounted for in the overall
   establishment time.

1.3.3. Planning Tool Operation

   Another portion of the time is consumed by planning tools that run
   simulations using heuristic algorithms to find an optimized placement
   for the required circuits. These planning tools can require a
   significant running time, sometimes on the order of days.

   These simulations are, in general, executed for a set of demands for
   circuits, i.e., a batch mode, to improve the optimality of network
   resource usage and other parameters. Today, we do not really have a
   means to reduce this simulation time. On the contrary, to support
   fast, on-line, circuit establishment, this phase may be invoked more
   frequently, i.e., we will not "batch up" as many connection requests
   before we plan out the corresponding circuits. This means that the
   network may need to be re-optimized periodically, implying that the
   signaling should support re-optimization with minimum impact to
   existing services.

1.3.4. Circuit Provisioning

   Once the first three steps discussed above have been completed, the
   operator must provision the circuits using the outputs of the
   planning process. The time required for provisioning varies greatly.
   It can be fairly short, on the order of a few minutes, if the
   operators already have tools that help them to do the provisioning

over heterogeneous equipment. Otherwise, the process can take days.
Developing these tools for each new piece of equipment and each
vendor is a significant burden on the service provider. A
standardized interface for provisioning, such as GMPLS signaling,
could significantly reduce or eliminate this development burden. In
general, provisioning is a batched activity, i.e., a few times per
week an operator provisions a set of circuits. GMPLS will reduce
this provisioning time from a few minutes to a few seconds and could
help to transform this periodic process into a real-time process.

When a circuit is provisioned, it is not delivered directly to a
client. Rather, the operator first tests its performance and
behavior and, if successful, delivers the circuit to the client.
This testing phase lasts, in general, up to 24 hours. The operator
installs test equipment at each end and uses pre-defined test streams
to verify performance. If successful, the circuit is officially
accepted by the client. To speed up the verification (sometimes
known as "proving") process, it would be necessary to support some
form of automated performance testing.

1.4. Centralized Approach versus Distributed Approach

Whether a centralized approach or a distributed approach will be used
to control SDH/SONET networks is an open question, since each
approach has its merits. The application of GMPLS to SDH/SONET
networks does not preclude either model, although GMPLS is itself a
distributed technology.

The basic tradeoff between the centralized and distributed approaches
is that of complexity of the network elements versus that of the
network management system (NMS). Since adding functionality to
existing SDH/SONET network elements may not be possible, a
centralized approach may be needed in some cases. The main issue
facing centralized control via an NMS is one of scalability. For
instance, this approach may be limited in the number of network
elements that can be managed (e.g., one thousand). It is, therefore,
quite common for operators to deploy several NMS in parallel at the
Network Management Layer, each managing a different zone. In that
case, however, a Service Management Layer must be built on the top of
several individual NMS to take care of end-to-end on-demand services.
On the other hand, in a complex and/or dense network, restoration
could be faster with a distributed approach than with a centralized
approach.

Let's now look at how the major control plane functional components
are handled via the centralized and distributed approaches:

1.4.1. Topology Discovery and Resource Dissemination

   Currently, an NMS maintains a consistent view of all the networking
   layers under its purview. This can include the physical topology,
   such as information about fibers and ducts. Since most of this
   information is entered manually, it remains error prone.

   A link state GMPLS routing protocol, on the other hand, could perform
   automatic topology discovery and disseminate the topology as well as
   resource status. This information would be available to all nodes in
   the network, and hence also the NMS. Hence, one can look at a
   continuum of functionality between manually provisioned topology
   information (of which there will always be some) and fully automated
   discovery and dissemination (as in a link state protocol). Note
   that, unlike the IP datagram case, a link state routing protocol
   applied to the SDH/SONET network does not have any service impacting
   implications. This is because in the SDH/SONET case, the circuit is
   source-routed (so there can be no loops), and no traffic is
   transmitted until a circuit has been established and an
   acknowledgement received at the source.

1.4.2. Path Computation (Route Determination)

   In the SDH/SONET case, unlike the IP datagram case, there is no need
   for network elements to all perform the same path calculation [6].
   In addition, path determination is an area for vendors to provide a
   potentially significant value addition in terms of network
   efficiency, reliability, and service differentiation. In this sense,
   a centralized approach to path computation may be easier to operate
   and upgrade. For example, new features such as new types of path
   diversity or new optimization algorithms can be introduced with a
   simple NMS software upgrade. On the other hand, updating switches
   with new path computation software is a more complicated task. In
   addition, many of the algorithms can be fairly computationally
   intensive and may be completely unsuitable for the embedded
   processing environment available on most switches. In restoration
   scenarios, the ability to perform a reasonably sophisticated level of
   path computation on the network element can be particularly useful
   for restoring traffic during major network faults.

1.4.3. Connection Establishment (Provisioning)

   The actual setting up of circuits, i.e., a coupled collection of
   cross connects across a network, can be done either via the NMS
   setting up individual cross connects or via a "soft permanent LSP"
   (SPLSP) type approach. In the SPLSP approach, the NMS may just kick
   off the connection at the "ingress" switch with GMPLS signaling
   setting up the connection from that point onward. Connection

establishment is the trickiest part to distribute, however, since
errors in the connection setup/tear down process are service
impacting.

The table below compares the two approaches to connection
establishment.

Table 1. Qualitative comparison between centralized and distributed
approaches.

Distributed approach	Centralized approach
Packet-based control plane (like GMPLS or PNNI) useful? Do we really need it? Being added/specified by several standardization bodies	Management plane like TMN or SNMP Always needed! Already there, proven and understood.
High survivability (e.g., in case of partition)	Potential single point(s) of failure
Distributed load	Bottleneck: #requests and actions to/from NMS
Individual local routing decision	Centralized routing decision, can be done per block of requests
Routing scalable as for the Internet	Assumes a few big administrative domains
Complex to change routing protocol/algorithm	Very easy local upgrade (non-intrusive)
Requires enhanced routing protocol (traffic engineering)	Better consistency
Ideal for inter-domain	Not inter-domain friendly
Suitable for very dynamic demands	For less dynamic demands (longer lived)
Probably faster to restore, but more difficult to have reliable restoration.	Probably slower to restore,but could effect reliable restoration.
High scalability (hierarchical)	Limited scalability: #nodes, links, circuits, messages

```
      Planning (optimization)          Planning is a background
      harder to achieve                centralized activity

      Easier future integration
      with other control plane
      layers
```

1.5. Why SDH/SONET Will Not Disappear Tomorrow

   As IP traffic becomes the dominant traffic transported over the
   transport infrastructure, it is useful to compare the statistical
   multiplexing of IP with the time division multiplexing of SDH and
   SONET.

   Consider, for instance, a scenario where IP over WDM is used
   everywhere and lambdas are optically switched. In such a case, a
   carrier's carrier would sell dynamically controlled lambdas with each
   customers building their own IP backbones over these lambdas.

   This simple model implies that a carrier would sell lambdas instead
   of bandwidth. The carrier's goal will be to maximize the number of
   wavelengths/lambdas per fiber, with each customer having to fully
   support the cost for each end-to-end lambda whether or not the
   wavelength is fully utilized. Although, in the near future, we may
   have technology to support up to several hundred lambdas per fiber, a
   world where lambdas are so cheap and abundant that every individual
   customer buys them, from one point to any other point, appears an
   unlikely scenario today.

   More realistically, there is still room for a multiplexing technology
   that provides circuits with a lower granularity than a wavelength.
   (Not everyone needs a minimum of 10 Gbps or 40 Gbps per circuit, and
   IP does not yet support all telecom applications in bulk
   efficiently.)

   SDH and SONET possess a rich multiplexing hierarchy that permits
   fairly fine granularity and that provides a very cheap and simple
   physical separation of the transported traffic between circuits,
   i.e., QoS. Moreover, even IP datagrams cannot be transported
   directly over a wavelength. A framing or encapsulation is always
   required to delimit IP datagrams. The Total Length field of an IP
   header cannot be trusted to find the start of a new datagram, since
   it could be corrupted and would result in a loss of synchronization.
   The typical framing used today for IP over Dense WDM (DWDM) is
   defined in RFC1619/RFC2615 and is known as POS (Packet Over
   SDH/SONET), i.e., IP over PPP (in High-Level Data Link Control
   (HDLC)-like format) over SDH/SONET. SDH and SONET are actually
   efficient encapsulations for IP. For instance, with an average IP

datagram length of 350 octets, an IP over Gigabit Ethernet (GbE)
encapsulation using an 8B/10B encoding results in 28% overhead, an
IP/ATM/SDH encapsulation results in 22% overhead, and an IP/PPP/SDH
encapsulation results in only 6% overhead.

Any encapsulation of IP over WDM should, in the data plane, at least
provide the following: error monitoring capabilities (to detect
signal degradation); error correction capabilities, such as FEC
(Forward Error Correction) that are particularly needed for ultra
long haul transmission; and sufficient timing information, to allow
robust synchronization (that is, to detect the beginning of a
packet). In the case where associated signaling is used (that is,
where the control and data plane topologies are congruent), the
encapsulation should also provide the capacity to transport
signaling, routing, and management messages, in order to control the
optical switches. Rather, SDH and SONET cover all these aspects
natively, except FEC, which tends to be supported in a proprietary
way. (We note, however, that associated signaling is not a
requirement for the GMPLS-based control of SDH/SONET networks.
Rather, it is just one option. Non associated signaling, as would
happen with an out-of-band control plane network is another equally
valid option.)

Since IP encapsulated in SDH/SONET is efficient and widely used, the
only real difference between an IP over WDM network and an IP over
SDH over WDM network is the layers at which the switching or
forwarding can take place. In the first case, it can take place at
the IP and optical layers. In the second case, it can take place at
the IP, SDH/SONET, and optical layers.

Almost all transmission networks today are based on SDH or SONET. A
client is connected either directly through an SDH or SONET interface
or through a PDH interface, the PDH signal being transported between
the ingress and the egress interfaces over SDH or SONET. What we are
arguing here is that it makes sense to do switching or forwarding at
all these layers.

2. GMPLS Applied to SDH/SONET

2.1. Controlling the SDH/SONET Multiplex

Controlling the SDH/SONET multiplex implies deciding which of the
different switchable components of the SDH/SONET multiplex we wish to
control using GMPLS. Essentially, every SDH/SONET element that is
referenced by a pointer can be switched. These component signals are
the VC-4, VC-3, VC-2, VC-12, and VC-11 in the SDH case; and the VT
and STS SPEs in the SONET case. The SPEs in SONET do not have

individual names, although they can be referred to simply as VT-N
SPEs. We will refer to them by identifying the structure that
contains them, namely STS-1, VT-6, VT-3, VT-2, and VT-1.5.

The STS-1 SPE corresponds to a VC-3, a VT-6 SPE corresponds to a VC-
2, a VT-2 SPE corresponds to a VC-12, and a VT-1.5 SPE corresponds to
a VC-11. The SONET VT-3 SPE has no correspondence in SDH, however
SDH's VC-4 corresponds to SONET's STS-3c SPE.

In addition, it is possible to concatenate some of the structures
that contain these elements to build larger elements. For instance,
SDH allows the concatenation of X contiguous AU-4s to build a VC-4-Xc
and of m contiguous TU-2s to build a VC-2-mc. In that case, a VC-4-
Xc or a VC-2-mc can be switched and controlled by GMPLS. SDH also
defines virtual (non-contiguous) concatenation of TU-2s; however, in
that case, each constituent VC-2 is switched individually.

2.2. SDH/SONET LSR and LSP Terminology

Let an SDH or SONET Terminal Multiplexer (TM), Add-Drop Multiplexer
(ADM), or cross-connect (i.e., a switch) be called an SDH/SONET LSR.
An SDH/SONET path or circuit between two SDH/SONET LSRs now becomes a
GMPLS LSP. An SDH/SONET LSP is a logical connection between the
point at which a tributary signal (client layer) is adapted into its
virtual container, and the point at which it is extracted from its
virtual container.

To establish such an LSP, a signaling protocol is required to
configure the input interface, switch fabric, and output interface of
each SDH/SONET LSR along the path. An SDH/SONET LSP can be point-
to-point or point-to-multipoint, but not multipoint-to-point, since
no merging is possible with SDH/SONET signals.

To facilitate the signaling and setup of SDH/SONET circuits, an
SDH/SONET LSR must, therefore, identify each possible signal
individually per interface, since each signal corresponds to a
potential LSP that can be established through the SDH/SONET LSR. It
turns out, however, that not all SDH signals correspond to an LSP and
therefore not all of them need be identified. In fact, only those
signals that can be switched need identification.

3. Decomposition of the GMPLS Circuit-Switching Problem Space

Although those familiar with GMPLS may be familiar with its
application in a variety of application areas (e.g., ATM, Frame
Relay, and so on), here we quickly review its decomposition when
applied to the optical switching problem space.

(i) Information needed to compute paths must be made globally
available throughout the network. Since this is done via the link
state routing protocol, any information of this nature must either be
in the existing link state advertisements (LSAs) or the LSAs must be
supplemented to convey this information. For example, if it is
desirable to offer different levels of service in a network, based on
whether a circuit is routed over SDH/SONET lines that are ring
protected versus being routed over those that are not ring protected
(differentiation based on reliability), the type of protection on a
SDH/SONET line would be an important topological parameter that would
have to be distributed via the link state routing protocol.

(ii) Information that is only needed between two "adjacent" switches
for the purposes of connection establishment is appropriate for
distribution via one of the label distribution protocols. In fact,
this information can be thought of as the "virtual" label. For
example, in SONET networks, when distributing information to switches
concerning an end-to-end STS-1 path traversing a network, it is
critical that adjacent switches agree on the multiplex entry used by
this STS-1 (but this information is only of local significance
between those two switches). Hence, the multiplex entry number in
this case can be used as a virtual label. Note that the label is
virtual, in that it is not appended to the payload in any way, but it
is still a label in the sense that it uniquely identifies the signal
locally on the link between the two switches.

(iii) Information that all switches in the path need to know about a
circuit will also be distributed via the label distribution protocol.
Examples of such information include bandwidth, priority, and
preemption.

(iv) Information intended only for end systems of the connection.
Some of the payload type information may fall into this category.

4. GMPLS Routing for SDH/SONET

Modern SDH/SONET transport networks excel at interoperability in the
performance monitoring (PM) and fault management (FM) areas [7], [8].
They do not, however, interoperate in the areas of topology discovery
or resource status. Although link state routing protocols, such as
IS-IS and OSPF, have been used for some time in the IP world to
compute destination-based next hops for routes (without routing
loops), they are particularly valuable for providing timely topology
and network status information in a distributed manner, i.e., at any
network node. If resource utilization information is disseminated
along with the link status (as done in ATM's PNNI routing protocol),
then a very complete picture of network status is available to a
network operator for use in planning, provisioning, and operations.

The information needed to compute the path a connection will take
through a network is important to distribute via the routing
protocol. In the TDM case, this information includes, but is not
limited to: the available capacity of the network links, the
switching and termination capabilities of the nodes and interfaces,
and the protection properties of the link. This is what is being
proposed in the GMPLS extensions to IP routing protocols [9], [10],
[11].

When applying routing to circuit switched networks, it is useful to
compare and contrast this situation with the datagram routing case
[12]. In the case of routing datagrams, all routes on all nodes must
be calculated exactly the same to avoid loops and "black holes". In
circuit switching, this is not the case since routes are established
per circuit and are fixed for that circuit. Hence, unlike the
datagram case, routing is not service impacting in the circuit
switched case. This is helpful because, to accommodate the optical
layer, routing protocols need to be supplemented with new
information, as compared to the datagram case. This information is
also likely to be used in different ways for implementing different
user services. Due to the increase in information transferred in the
routing protocol, it may be useful to separate the relatively static
parameters concerning a link from those that may be subject to
frequent changes. However, the current GMPLS routing extensions [9],
[10], [11] do not make such a separation.

Indeed, from the carriers' perspective, the up-to-date dissemination
of all link properties is essential and desired, and the use of a
link-state routing protocol to distribute this information provides
timely and efficient delivery. If GMPLS-based networks got to the
point that bandwidth updates happen very frequently, it makes sense,
from an efficiency point of view, to separate them out for update.
This situation is not yet seen in actual networks; however, if GMPLS
signaling is put into widespread use then the need could arise.

4.1. Switching Capabilities

The main switching capabilities that characterize an SDH/SONET end
system and thus need to be advertised via the link state routing
protocol are: the switching granularity, supported forms of
concatenation, and the level of transparency.

4.1.1. Switching Granularity

From references [2], [3], and the overview section on SDH/SONET we
see that there are a number of different signals that compose the
SDH/SONET hierarchies. Those signals that are referenced via a
pointer (i.e., the VCs in SDH and the SPEs in SONET) will actually be

switched within an SDH/SONET network. These signals are subdivided
into lower order signals and higher order signals as shown in Table
2.

Table 2. SDH/SONET switched signal groupings.

Signal Type	SDH	SONET
Lower Order	VC-11, VC-12, VC-2	VT-1.5 SPE, VT-2 SPE, VT-3 SPE, VT-6 SPE
Higher Order	VC-3, VC-4	STS-1 SPE, STS-3c SPE

Manufacturers today differ in the types of switching capabilities
their systems support. Many manufacturers today switch signals
starting at VC-4 for SDH or STS-1 for SONET (i.e., down the basic
frame) and above (see Section 5.1.2 on concatenation), but they do
not switch lower order signals. Some of them only allow the
switching of entire aggregates (concatenated or not) of signals such
as 16 VC-4s, i.e., a complete STM-16, and nothing finer. Some go
down to the VC-3 level for SDH. Finally, some offer highly
integrated switches that switch at the VC-3/STS-1 level down to lower
order signals such as VC-12s. In order to cover the needs of all
manufacturers and operators, GMPLS signaling ([4], [5]) covers both
higher order and lower order signals.

4.1.2. Signal Concatenation Capabilities

As stated in the SDH/SONET overview, to transport tributary signals
with rates in excess of the basic STM-1/STS-1 signal, the VCs/SPEs
can be concatenated, i.e., glued together. Different types of
concatenations are defined: contiguous standard concatenation,
arbitrary concatenation, and virtual concatenation with different
rules concerning their size, placement, and binding.

Standard SONET concatenation allows the concatenation of M x STS-1
signals within an STS-N signal with M <= N, and M = 3, 12, 48, 192,
STS-Mc. The STS-Mc notation is shorthand for describing an STS-M
signal whose SPEs have been concatenated. The multiplexing
procedures for SDH and SONET are given in references [2] and [3],
respectively. Constraints are imposed on the size of STS-Mc signals,
i.e., they must be a multiple of 3, and on their starting location
and interleaving.

This has the following advantages: (a) restriction to multiples of 3
helps with SDH compatibility (there is no STS-1 equivalent signal in
SDH); (b) the restriction to multiples of 3 reduces the number of
connection types; (c) the restriction on the placement and
interleaving could allow more compact representation of the "label";

The major disadvantages of these restrictions are: (a) Limited
flexibility in bandwidth assignment (somewhat inhibits finer grained
traffic engineering). (b) The lack of flexibility in starting time
slots for STS-Mc signals and in their interleaving (where the rest of
the signal gets put in terms of STS-1 slot numbers) leads to the
requirement for re-grooming (due to bandwidth fragmentation).

Due to these disadvantages, some SONET framer manufacturers now
support "flexible" or arbitrary concatenation. That is, they support
concatenation with no restrictions on the size of an STS-Mc (as long
as M <= N) and no constraints on the STS-1 timeslots used to convey
it, i.e., the signals can use any combination of available time
slots.

Standard and flexible concatenations are network services, while
virtual concatenation is an SDH/SONET end-system service approved by
the Committee T1 of ANSI [3] and the ITU-T [2]. The essence of this
service is to have SDH/SONET end systems "glue" together the VCs or
SPEs of separate signals, rather than requiring that the signals be
carried through the network as a single unit. In one example of
virtual concatenation, two end systems supporting this feature could
essentially "inverse multiplex" two STS-1s into an STS-1-2v for the
efficient transport of 100 Mbps Ethernet traffic. Note that this
inverse multiplexing process (or virtual concatenation) can be
significantly easier to implement with SDH/SONET than packet switched
circuits, because ensuring that timing and in-order frame delivery is
preserved may be simpler to establish using SDH/SONET, rather than
packet switched circuits, where more sophisticated techniques may be
needed.

Since virtual concatenation is provided by end systems, it is
compatible with existing SDH/SONET networks. Virtual concatenation
is defined for both higher order signals and low order signals.
Table 3 shows the nomenclature and capacity for several lower-order
virtually concatenated signals contained within different higher-
order signals.

Table 3. Capacity of Virtually Concatenated VTn-Xv (9/G.707)

	Carried In	X	Capacity	In steps of
VT1.5/ VC-11-Xv	STS-1/VC-3	1 to 28	1600kbit/s to 44800kbit/s	1600kbit/s
VT2/ VC-12-Xv	STS-1/VC-3	1 to 21	2176kbit/s to 45696kbit/s	2176kbit/s
VT1.5/ VC-11-Xv	STS-3c/VC-4	1 to 64	1600kbit/s to 102400kbit/s	1600kbit/s
VT2/ VC-12-Xv	STS-3c/VC-4	1 to 63	2176kbit/s to 137088kbit/s	2176kbit/s

4.1.3. SDH/SONET Transparency

   The purposed of SDH/SONET is to carry its payload signals in a
   transparent manner. This can include some of the layers of SONET
   itself. An example of this is a situation where the path overhead
   can never be touched, since it actually belongs to the client. This
   was another reason for not coding an explicit label in the SDH/SONET
   path overhead. It may be useful to transport, multiplex and/or
   switch lower layers of the SONET signal transparently.

   As mentioned in the introduction, SONET overhead is broken into three
   layers: Section, Line, and Path. Each of these layers is concerned
   with fault and performance monitoring. The Section overhead is
   primarily concerned with framing, while the Line overhead is
   primarily concerned with multiplexing and protection. To perform
   pipe multiplexing (that is, multiplexing of 50 Mbps or 150 Mbps
   chunks), a SONET network element should be line terminating.
   However, not all SONET multiplexers/switches perform SONET pointer
   adjustments on all the STS-1s contained within a higher order SONET
   signal passing through them. Alternatively, if they perform pointer
   adjustments, they do not terminate the line overhead. For example, a
   multiplexer may take four SONET STS-48 signals and multiplex them
   onto an STS-192 without performing standard line pointer adjustments
   on the individual STS-1s. This can be looked at as a service since
   it may be desirable to pass SONET signals, like an STS-12 or STS-48,
   with some level of transparency through a network and still take
   advantage of TDM technology. Transparent multiplexing and switching
   can also be viewed as a constraint, since some multiplexers and
   switches may not switch with as fine a granularity as others. Table
   4 summarizes the levels of SDH/SONET transparency.

Table 4. SDH/SONET transparency types and their properties.

Transparency Type	Comments
Path Layer (or Line Terminating)	Standard higher order SONET path switching. Line overhead is terminated or modified.
Line Level (or Section Terminating)	Preserves line overhead and switches the entire line multiplex as a whole. Section overhead is terminated or modified.
Section layer	Preserves all section overhead, Basically does not modify/terminate any of the SDH/SONET overhead bits.

4.2. Protection

   SONET and SDH networks offer a variety of protection options at both
   the SONET line (SDH multiplex section) and SDH/SONET path level [7],
   [8]. Standardized SONET line level protection techniques include:
   Linear 1+1 and linear 1:N automatic protection switching (APS) and
   both two-fiber and four-fiber bi-directional line switched rings
   (BLSRs). At the path layer, SONET offers uni-directional path
   switched ring protection. Likewise, standardized SDH multiplex
   section protection techniques include linear 1+1 and 1:N automatic p
   protection switching and both two-fiber and four-fiber bi-directional
   MS-SPRings (Multiplex Section-Shared Protection Rings).

   At the path layer, SDH offers SNCP (sub-network connection
   protection) ring protection.

   Both ring and 1:N line protection also allow for "extra traffic" to
   be carried over the protection line when that line is not being used,
   i.e., when it is not carrying traffic for a failed working line.
   These protection methods are summarized in Table 5. It should be
   noted that these protection methods are completely separate from any
   GMPLS layer protection or restoration mechanisms.

Table 5. Common SDH/SONET protection mechanisms.

Protection Type	Extra Traffic Optionally Supported	Comments
1+1 Unidirectional	No	Requires no coordination between the two ends of the circuit. Dedicated protection line.
1+1 Bi-directional	No	Coordination via K byte protocol. Lines must be consistently configured. Dedicated protection line.
1:1	Yes	Dedicated protection.
1:N	Yes	One Protection line shared by N working lines
4F-BLSR (4 fiber bi-directional line switched ring)	Yes	Dedicated protection, with alternative ring path.
2F-BLSR (2 fiber bi-directional line switched ring)	Yes	Dedicated protection, with alternative ring path
UPSR (uni-directional path switched ring)	No	Dedicated protection via alternative ring path. Typically used in access networks.

It may be desirable to route some connections over lines that support
protection of a given type, while others may be routed over
unprotected lines, or as "extra traffic" over protection lines.
Also, to assist in the configuration of these various protection
methods, it can be extremely valuable to advertise the link
protection attributes in the routing protocol, as is done in the
current GMPLS routing protocols. For example, suppose that a 1:N
protection group is being configured via two nodes. One must make

sure that the lines are "numbered the same" with respect to both ends
of the connection, or else the APS (K1/K2 byte) protocol will not
correctly operate.

Table 6. Parameters defining protection mechanisms.

Protection Related Link Information	Comments
Protection Type	Indicates which of the protection types delineated in Table 5.
Protection Group Id	Indicates which of several protection groups (linear or ring) that a node belongs to. Must be unique for all groups that a node participates in
Working line number	Important in 1:N case and to differentiate between working and protection lines
Protection line number	Used to indicate if the line is a protection line.
Extra Traffic Supported	Yes or No
Layer	If this protection parameter is specific to SONET then this parameter is unneeded, otherwise it would indicate the signal layer that the protection is applied.

An open issue concerning protection is the extent of information
regarding protection that must be disseminated. The contents of
Table 6 represent one extreme, while a simple enumerated list
(Extra-Traffic/Protection line, Unprotected, Shared (1:N)/Working
line, Dedicated (1:1, 1+1)/Working Line, Enhanced (Ring) /Working
Line) represents the other.

There is also a potential implication for link bundling [13], [15]
that is, for each link, the routing protocol could advertise whether
that link is a working or protection link and possibly some
parameters from Table 6. A possible drawback of this scheme is that
the routing protocol would be burdened with advertising properties
even for those protection links in the network that could not, in
fact, be used for routing working traffic, e.g., dedicated protection
links. An alternative method would be to bundle the working and

protection links together, and advertise the bundle instead. Now,
for each bundled link, the protocol would have to advertise the
amount of bandwidth available on its working links, as well as the
amount of bandwidth available on those protection links within the
bundle that were capable of carrying "extra traffic". This would
reduce the amount of information to be advertised. An issue here
would be to decide which types of working and protection links to
bundle together. For instance, it might be preferable to bundle
working links (and their corresponding protection links) that are
"shared" protected separately from working links that are "dedicated"
protected.

4.3. Available Capacity Advertisement

   Each SDH/SONET LSR must maintain an internal table per interface that
   indicates each signal in the multiplex structure that is allocated at
   that interface. This internal table is the most complete and
   accurate view of the link usage and available capacity.

   For use in path computation, this information needs to be advertised
   in some way to all other SDH/SONET LSRs in the same domain. There is
   a trade off to be reached concerning: the amount of detail in the
   available capacity information to be reported via a link state
   routing protocol, the frequency or conditions under which this
   information is updated, the percentage of connection establishments
   that are unsuccessful on their first attempt due to the granularity
   of the advertised information, and the extent to which network
   resources can be optimized. There are different levels of
   summarization that are being considered today for the available
   capacity information. At one extreme, all signals that are allocated
   on an interface could be advertised; while at the other extreme, a
   single aggregated value of the available bandwidth per link could be
   advertised.

   Consider first the relatively simple structure of SONET and its most
   common current and planned usage. DS1s and DS3s are the signals most
   often carried within a SONET STS-1. Either a single DS3 occupies the
   STS-1 or up to 28 DS1s (4 each within the 7 VT groups) are carried
   within the STS-1. With a reasonable VT1.5 placement algorithm within
   each node, it may be possible to just report on aggregate bandwidth
   usage in terms of number of whole STS-1s (dedicated to DS3s) used and
   the number of STS-1s dedicated to carrying DS1s allocated for this
   purpose. This way, a network optimization program could try to
   determine the optimal placement of DS3s and DS1s to minimize wasted
   bandwidth due to half-empty STS-1s at various places within the
   transport network. Similarly consider the set of super rate SONET
   signals (STS-Nc). If the links between the two switches support
   flexible concatenation, then the reporting is particularly

straightforward since any of the STS-1s within an STS-M can be used
to comprise the transported STS-Nc. However, if only standard
concatenation is supported, then reporting gets trickier since there
are constraints on where the STS-1s can be placed. SDH has still
more options and constraints, hence it is not yet clear which is the
best way to advertise bandwidth resource availability/usage in
SDH/SONET. At present, the GMPLS routing protocol extensions define
minimum and maximum values for available bandwidth, which allows a
remote node to make some deductions about the amount of capacity
available at a remote link and the types of signals it can
accommodate. However, due to the multiplexed nature of the signals,
reporting of bandwidth particular to signal types, rather than as a
single aggregate bit rate, may be desirable. For details on why this
may be the case, we refer the reader to ITU-T publications G.7715.1
[16] and to Chapter 12 of [17].

4.4. Path Computation

Although a link state routing protocol can be used to obtain network
topology and resource information, this does not imply the use of an
"open shortest path first" route [6]. The path must be open in the
sense that the links must be capable of supporting the desired signal
type and that capacity must be available to carry the signal. Other
constraints may include hop count, total delay (mostly propagation),
and underlying protection. In addition, it may be desirable to route
traffic in order to optimize overall network capacity, or
reliability, or some combination of the two. Dikstra's algorithm
computes the shortest path with respect to link weights for a single
connection at a time. This can be much different than the paths that
would be selected in response to a request to set up a batch of
connections between a set of endpoints in order to optimize network
link utilization. One can think of this along the lines of global or
local optimization of the network in time.

Due to the complexity of some of the connection routing algorithms
(high dimensionality, non-linear integer programming problems) and
various criteria by which one may optimize a network, it may not be
possible or desirable to run these algorithms on network nodes.
However, it may still be desirable to have some basic path
computation ability running on the network nodes, particularly for
use during restoration situations. Such an approach is in line with
the use of GMPLS for traffic engineering, but is much different than
typical OSPF or IS-IS usage where all nodes must run the same routing
algorithm.

5. LSP Provisioning/Signaling for SDH/SONET

   Traditionally, end-to-end circuit connections in SDH/SONET networks
   have been set up via network management systems (NMSs), which issue
   commands (usually under the control of a human operator) to the
   various network elements involved in the circuit, via an equipment
   vendor's element management system (EMS). Very little multi-vendor
   interoperability has been achieved via management systems. Hence,
   end-to-end circuits in a multi-vendor environment typically require
   the use of multiple management systems and the infamous configuration
   via "yellow sticky notes". As discussed in Section 3, a common
   signaling protocol -- such as RSVP with TE extensions or CR-LDP --
   appropriately extended for circuit switching applications, could
   therefore help to solve these interoperability problems. In this
   section, we examine the various components involved in the automated
   provisioning of SDH/SONET LSPs.

5.1. What Do We Label in SDH/SONET? Frames or Circuits?

   GMPLS was initially introduced to control asynchronous technologies
   like IP, where a label was attached to each individual block of data,
   such as an IP packet or a Frame Relay frame. SONET and SDH, however,
   are synchronous technologies that define a multiplexing structure
   (see Section 3), which we referred to as the SDH (or SONET)
   multiplex. This multiplex involves a hierarchy of signals, lower
   order signals embedded within successive higher order ones (see Fig.
   1). Thus, depending on its level in the hierarchy, each signal
   consists of frames that repeat periodically, with a certain number of
   byte time slots per frame.

   The question then arises: is it these frames that we label in GMPLS?
   It will be seen in what follows that each SONET or SDH "frame" need
   not have its own label, nor is it necessary to switch frames
   individually. Rather, the unit that is switched is a "flow"
   comprised of a continuous sequence of time slots that appear at a
   given position in a frame. That is, we switch an individual SONET or
   SDH signal, and a label associated with each given signal.

   For instance, the payload of an SDH STM-1 frame does not fully
   contain a complete unit of user data. In fact, the user data is
   contained in a virtual container (VC) that is allowed to float over
   two contiguous frames for synchronization purposes. The H1-H2-H3
   Au-n pointer bytes in the SDH overhead indicates the beginning of the
   VC in the payload. Thus, frames are now inter-related, since each
   consecutive pair may share a common virtual container. From the
   point of view of GMPLS, therefore, it is not the successive frames
   that are treated independently or labeled, but rather the entire user
   signal. An identical argument applies to SONET.

Observe also that the GMPLS signaling used to control the SDH/SONET
multiplex must honor its hierarchy. In other words, the SDH/SONET
layer should not be viewed as homogeneous and flat, because this
would limit the scope of the services that SDH/SONET can provide.
Instead, GMPLS tunnels should be used to dynamically and
hierarchically control the SDH/SONET multiplex. For example, one
unstructured VC-4 LSP may be established between two nodes, and later
lower order LSPs (e.g., VC-12) may be created within that higher
order LSP. This VC-4 LSP can, in fact, be established between two
non-adjacent internal nodes in an SDH network, and later advertised
by a routing protocol as a new (virtual) link called a Forwarding
Adjacency (FA) [14].

An SDH/SONET-LSR will have to identify each possible signal
individually per interface to fulfill the GMPLS operations. In order
to stay transparent, the LSR obviously should not touch the SDH/SONET
overheads; this is why an explicit label is not encoded in the
SDH/SONET overheads. Rather, a label is associated with each
individual signal. This approach is similar to the one considered
for lambda switching, except that it is more complex, since SONET and
SDH define a richer multiplexing structure. Therefore, a label is
associated with each signal, and is locally unique for each signal at
each interface. This signal could, and will most probably, occupy
different time-slots at different interfaces.

5.2. Label Structure in SDH/SONET

The signaling protocol used to establish an SDH/SONET LSP must have
specific information elements in it to map a label to the particular
signal type that it represents, and to the position of that signal in
the SDH/SONET multiplex. As we will see shortly, with a carefully
chosen label structure, the label itself can be made to function as
this information element.

In general, there are two ways to assign labels for signals between
neighboring SDH/SONET LSRs. One way is for the labels to be
allocated completely independently of any SDH/SONET semantics; e.g.,
labels could just be unstructured 16 or 32 bit numbers. In that
case, in the absence of appropriate binding information, a label
gives no visible information about the flow that it represents. From
a management and debugging point of view, therefore, it becomes
difficult to match a label with the corresponding signal, since , as
we saw in Section 6.1, the label is not coded in the SDH/SONET
overhead of the signal.

Another way is to use the well-defined and finite structure of the
SDH/SONET multiplexing tree to devise a signal numbering scheme that
makes use of the multiplex as a naming tree, and assigns each

multiplex entry a unique associated value. This allows the unique
identification of each multiplex entry (signal) in terms of its type
and position in the multiplex tree. By using this multiplex entry
value itself as the label, we automatically add SDH/SONET semantics
to the label! Thus, simply by examining the label, one can now
directly deduce the signal that it represents, as well as its
position in the SDH/SONET multiplex. We refer to this as multiplex-
based labeling. This is the idea that was incorporated in the GMPLS
signaling specifications for SDH/SONET [15].

5.3. Signaling Elements

In the preceding sections, we defined the meaning of an SDH/SONET
label and specified its structure. A question that arises naturally
at this point is the following. In an LSP or connection setup
request, how do we specify the signal for which we want to establish
a path (and for which we desire a label)?

Clearly, information that is required to completely specify the
desired signal and its characteristics must be transferred via the
label distribution protocol, so that the switches along the path can
be configured to correctly handle and switch the signal. This
information is specified in three parts [15], each of which refers to
a different network layer.

1. GENERALIZED_LABEL REQUEST (as in [4], [5]), which contains three
   parts: LSP Encoding Type, Switching Type, and G-PID.

The first specifies the nature/type of the LSP or the desired
SDH/SONET channel, in terms of the particular signal (or collection
of signals) within the SDH/SONET multiplex that the LSP represents,
and is used by all the nodes along the path of the LSP.

The second specifies certain link selection constraints, which
control, at each hop, the selection of the underlying link that is
used to transport this LSP.

The third specifies the payload carried by the LSP or SDH/SONET
channel, in terms of the termination and adaptation functions
required at the end points, and is used by the source and destination
nodes of the LSP.

2. SONET/SDH TRAFFIC_PARAMETERS (as in [15], Section 2.1) used as a
   SENDER_TSPEC/FLOWSPEC, which contains 7 parts: Signal Type,
   (Requested Contiguous Concatenation (RCC), Number of Contiguous
   Components (NCC), Number of Virtual Components (NVC)), Multiplier
   (MT), Transparency, and Profile.

The Signal Type indicates the type of elementary signal comprising
the LSP, while the remaining fields indicate transforms that can be
applied to the basic signal to build the final signal that
corresponds to the LSP actually being requested. For instance (see
[15] for details):

   - Contiguous concatenation (by using the RCC and NCC fields) can
     be optionally applied on the Elementary Signal, resulting in a
     contiguously concatenated signal.

   - Then, virtual concatenation (by using the NVC field) can be
     optionally applied on the Elementary Signal, resulting in a
     virtually concatenated signal.

   - Third, some transparency (by using the Transparency field) can
     be optionally specified when requesting a frame as a signal
     rather than an SPE- or VC-based signal.

   - Fourth, a multiplication (by using the Multiplier field) can be
     optionally applied either directly on the Elementary Signal or
     on the contiguously concatenated signal obtained from the first
     phase, or on the virtually concatenated signal obtained from the
     second phase, or on these signals combined with some
     transparency.

Transparency indicates precisely which fields in these overheads must
be delivered unmodified at the other end of the LSP. An ingress LSR
requesting transparency will pass these overhead fields that must be
delivered to the egress LSR without any change. From the ingress and
egress LSRs point of views, these fields must be seen as unmodified.

Transparency is not applied at the interfaces with the initiating and
terminating LSRs, but is only applied between intermediate LSRs.

The transparency field is used to request an LSP that supports the
requested transparency type; it may also be used to setup the
transparency process to be applied at each intermediate LSR.

Finally, the profile field is intended to specify particular
capabilities that must be supported for the LSP, for example
monitoring capabilities. However, no standard profile is currently
defined.

3. UPSTREAM_LABEL for Bi-directional LSP's (as in [4], [5]).

4. Local Link Selection, e.g., IF_ID_RSVP_HOP Object (as in [5]).

6. Summary and Conclusions

   We provided a detailed account of the issues involved in applying
   generalized GMPLS-based control (GMPLS) to TDM networks.

   We began with a brief overview of GMPLS and SDH/SONET networks,
   discussing current circuit establishment in TDM networks, and arguing
   why SDH/SONET technologies will not be "outdated" in the foreseeable
   future. Next, we looked at IP/MPLS applied to SDH/SONET networks,
   where we considered why such an application makes sense, and reviewed
   some GMPLS terminology as applied to TDM networks.

   We considered the two main areas of application of IP/MPLS methods to
   TDM networks, namely routing and signaling, and discussed how
   Generalized MPLS routing and signaling are used in the context of TDM
   networks. We reviewed in detail the switching capabilities of TDM
   equipment, and the requirement to learn about the protection
   capabilities of underlying links, and how these influence the
   available capacity advertisement in TDM networks.

   We focused briefly on path computation methods, pointing out that
   these were not subject to standardization. We then examined optical
   path provisioning or signaling, considering the issue of what
   constitutes an appropriate label for TDM circuits and how this label
   should be structured; and we focused on the importance of
   hierarchical label allocation in a TDM network. Finally, we reviewed
   the signaling elements involved when setting up a TDM circuit,
   focusing on the nature of the LSP, the type of payload it carries,
   and the characteristics of the links that the LSP wishes to use at
   each hop along its path for achieving a certain reliability.

7. Security Considerations

   The use of a control plane to provision connectivity through a
   SONET/SDH network shifts the security burden significantly from the
   management plane to the control plane. Before the introduction of a
   control plane, the communications that had to be secured were between
   the management stations (Element Management Systems or Network
   Management Systems) and each network element that participated in the
   network connection. After the introduction of the control plane, the
   only management plane communication that needs to be secured is that
   to the head-end (ingress) network node as the end-to-end service is
   requested. On the other hand, the control plane introduces a new
   requirement to secure signaling and routing communications between
   adjacent nodes in the network plane.

The security risk from impersonated management stations is
significantly reduced by the use of a control plane. In particular,
where unsecure versions of network management protocols such as SNMP
versions 1 and 2 were popular configuration tools in transport
networks, the use of a control plane may significantly reduce the
security risk of malicious and false assignment of network resources
that could cause the interception or disruption of data traffic.

On the other hand, the control plane may increase the number of
security relationships that each network node must maintain. Instead
of a single security relationship with its management element, each
network node must now maintain a security relationship with each of
its signaling and routing neighbors in the control plane.

There is a strong requirement for signaling and control plane
exchanges to be secured, and any protocols proposed for this purpose
must be capable of secure message exchanges. This is already the
case for the existing GMPLS routing and signaling protocols.

8. Acknowledgements

9. Informative References

   In the ITU references below, please see http://www.itu.int for
   availability of ITU documents. For ANSI references, please see the
   Library available through http://www.ansi.org.

   [1]   Rosen, E., Viswanathan, A., and R. Callon, "Multiprotocol Label
         Switching Architecture", RFC 3031, January 2001.

   [2]   G.707, Network Node Interface for the Synchronous Digital
         Hierarchy (SDH), International Telecommunication Union, March
         1996.

   [3]   ANSI T1.105-1995, Synchronous Optical Network (SONET) Basic
         Description including Multiplex Structure, Rates, and Formats,
         American National Standards Institute.

   [4]   Berger, L., "Generalized Multi-Protocol Label Switching (GMPLS)
         Signaling Functional Description", RFC 3471, January 2003.

   [5]   Berger, L., "Generalized Multi-Protocol Label Switching (GMPLS)
         Signaling Resource ReserVation Protocol-Traffic Engineering
         (RSVP-TE) Extensions", RFC 3473, January 2003.

   [6]   Bernstein, G., Yates, J., Saha, D., "IP-Centric Control and
         Management of Optical Transport Networks," IEEE Communications
         Mag., Vol. 40, Issue 10, October 2000.

   [7]   ANSI T1.105.01-1995, Synchronous Optical Network (SONET)
         Automatic Protection Switching, American National Standards
         Institute.

   [8]   G.841, Types and Characteristics of SDH Network Protection
         Architectures, ITU-T, July 1995.

   [9]   Kompella, K., Ed. and Y. Rekhter, Ed., "Routing Extensions in
         Support of Generalized Multi-Protocol Label Switching (GMPLS)",
         RFC 4202, October 2005.

   [10] Kompella, K., Ed. and Y. Rekhter, Ed., "OSPF Extensions in
         Support of Generalized Multi-Protocol Label Switching (GMPLS)",
         RFC 4203, October 2005.

   [11] Kompella, K., Ed. and Y. Rekhter, Ed., "Intermediate System to
         Intermediate System (IS-IS) Extensions in Support of Generalized
         Multi-Protocol Label Switching (GMPLS)", RFC 4205, October 2005.

   [12] Bernstein, G., Sharma, V., Ong, L., "Inter-domain Optical
        Routing," OSA J. of Optical Networking, vol. 1, no. 2, pp. 80-
        92.

   [13] Kompella, K., Rekhter, Y. and L. Berger, "Link Bundling in MPLS
        Traffic Engineering (TE)", RFC 4201, October 2005.

   [14] Kompella, K. and Y. Rekhter, "Label Switched Paths (LSP)
        Hierarchy with Generalized Multi-Protocol Label Switching
        (GMPLS) Traffic Engineering (TE)", RFC 4206, October 2005.

   [15] Mannie, E. and D. Papadimitriou, "Generalized Multi-Protocol
        Label Switching (GMPLS) Extensions for Synchronous Optical
        Network (SONET) and Synchronous Digital Hierarchy (SDH)
        Control", RFC 3946, October 2004.

   [16] G.7715.1, ASON Routing Architecture and Requirements for Link-
        State Protocols, International Telecommunications Union,
        February 2004.

   [17] Bernstein, G., Rajagopalan, R., and Saha, D., "Optical Network
        Control: Protocols, Architectures, and Standards," Addison-
        Wesley, July 2003.

10. Acronyms

   ANSI   - American National Standards Institute
   APS   - Automatic Protection Switching
   ATM   - Asynchronous Transfer Mode
   BLSR   - Bi-directional Line Switch Ring
   CPE   - Customer Premise Equipment
   DLCI   - Data Link Connection Identifier
   ETSI   - European Telecommunication Standards Institute
   FEC   - Forwarding Equivalency Class
   GMPLS   - Generalized MPLS
   IP   - Internet Protocol
   IS-IS   - Intermediate System to Intermediate System (RP)
   LDP   - Label Distribution Protocol
   LSP   - Label Switched Path
   LSR   - Label Switching Router
   MPLS   - Multi-Protocol Label Switching
   NMS   - Network Management System
   OSPF   - Open Shortest Path First (RP)
   PNNI   - Private Network Node Interface
   PPP   - Point to Point Protocol
   QoS   - Quality of Service
   RP   - Routing Protocol
   RSVP   - ReSerVation Protocol
   SDH   - Synchronous Digital Hierarchy
   SNMP   - Simple Network Management Protocol
   SONET   - Synchronous Optical NETworking
   SPE   - SONET Payload Envelope
   STM   - Synchronous Transport Module (or Terminal Multiplexer)
   STS   - Synchronous Transport Signal
   TDM   - Time Division Multiplexer
   TE   - Traffic Engineering
   TMN   - Telecommunication Management Network
   UPSR   - Uni-directional Path Switch Ring
   VC   - Virtual Container (SDH) or Virtual Circuit
   VCI   - Virtual Circuit Identifier (ATM)
   VPI   - Virtual Path Identifier (ATM)
   VT   - Virtual Tributary
   WDM   - Wavelength-Division Multiplexing

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