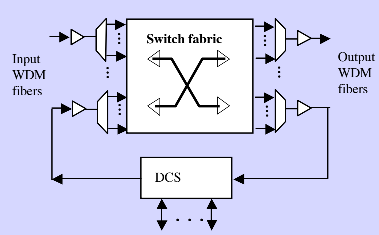
Chapter 9: Wavelength Routing Optical Networks

TOPICS

- Wavelength routing networks
- Protection schemes
- G.709 - The digital wrapper
- Control plane architectures
- GMPLS
- OIF UNI

A wavelength routing network

This is an optical network that consists of OXCs interconnected by WDM fibers, with each fiber consisting of W wavelengths



OXC functionality

- It switches optically all the incoming wavelengths of the input fibers to the outgoing wavelengths of the output fibers.
- For instance, it can switch the optical signal on incoming wavelength λ_i of input fiber k to the outgoing wavelength λ_i of output fiber m.

Converters:

If it is equipped with converters, it can also switch the optical signal of the incoming wavelength λ_i of input fiber k to another outgoing wavelength λ_j of the output fiber m.

This happens when the wavelength λ_i of the output fiber m is in use.

Optical add/drop multiplexer (OADM):

An OXC can also be used as an OADM. That is, it can terminate the optical signal of a number of incoming wavelengths and insert new optical signals on the same wavelengths in an output port.

The remaining incoming wavelengths are switched through as described above.

Transparent and Opaque Switches

Transparent switch:

The incoming wavelengths are switched to the output fibers optically, without having to convert them to the electrical domain.

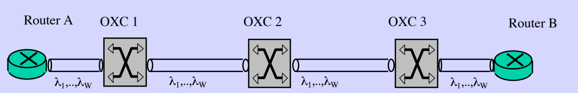
Opaque switch:

The input optical signals are converted to electrical signals, from where the packets are extracted. Packets are switched using a packet switch, and then they are transmitted out of the switch in the optical domain.

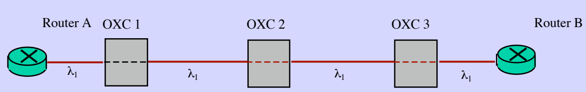
Lightpaths

- Wavelength routing networks are circuit-switched networks.
- In order for a user to send data to a another user, a connection has to be first setup.
- This connection is a circuit-switched connection and it is established by allocating a wavelength on each hop along the connection's path

An example of a lightpath



A three-node wavelength routing network



A lightpath between routers A and B

The wavelength continuity constraint

- When establishing a lightpath over a wavelength routing network, the same wavelength has to be used on every hop along the path.
- If the required wavelength is not available at the outgoing fiber of an OXC through which the lightpath has to be routed, then the establishment of the lightpath is blocked, and a notification message is sent back to the user.

Converters

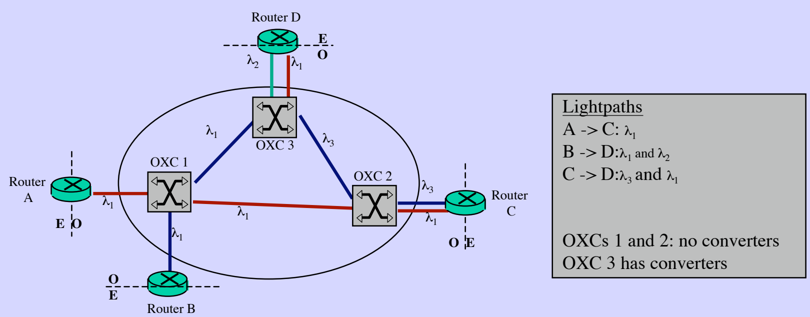
- In order to decrease the probability that a lightpath is blocked, the OXC can be equipped with converters.
- A converter can transform the optical signal transmitted over a wavelength to another wavelength.

In an OXC, for each output fiber with W wavelengths, there may be c converters, where $0 \le c \le W$.

- *No conversion:* c=0
- *Partial conversion:* 0 < c <W
- *Full conversion:* c=W

A converter can only transform a signal on a wavelength λ to another wavelength which is within a few nm from wavelength λ.

An example of different lightpaths



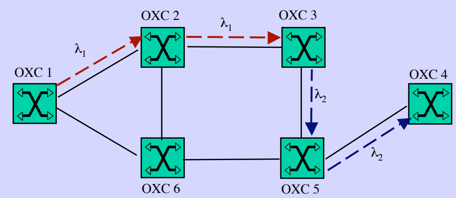
Traffic grooming

- A lightpath is exclusively used by a single client.
- Often the bandwidth a client requires is significantly less than the wavelength's bandwidth. This means that part of the lightpath's bandwidth is unused. Also, the user pays for more bandwidth than required.
- Traffic grooming permits mane user to share the same lightpath.

Sub-rate units

- The bandwidth of a lightpath is divided into *sub-rate* units so that it can carry traffic streams transmitted at lower rates.
- For instance a 2.5 Gbps (OC-48) bandwidth can be available in sub-rate units of 50 Mbps (OC-1)
- A client can request one or more of these sub-rate units. This improves wavelength utilization and lowers user's costs.

An example of traffic grooming



- Established lightpaths:
  - OXC 1 to OXC 3
  - OXC 3 to OXC 4
- Wavelength capacity: 2.488 Gbps (OC-48/STM-16)
- 16 sub-rate units of 155 Mbps (OC3/STM-1)

- A user attached to OXC 1 that wants to transmit data to a user attached to OXC 3, can request any integer number of OC-3/STM-1 sub-rate units up to a total of 16.
- Additional lightpaths can be established between OXCs 1 and 3, if the traffic between these two OXCs exceeds 2.488 Gbps.

Traversing more than one lightpath:

- Let us consider a user attached to OXC 1 who requests a connection to a user attached to OXC 4 for four sub-rate units.
- In this case, a new lightpath has to be established between OXCs 1 and 4, say, over OXCs 6 and 5.

- Alternatively, the connection can be routed through the two lightpaths (OXC 1 -> OXC 3 and OXC 3 -> OXC 4).
- Provided that there is free capacity on each lightpath and OXC 3 is equipped with a SONET/SDH DCS which permits it to extract the data stream from the incoming SONET/SDH frames on the first lightpath and place it into the SONET/SDH frames of the second lightpath.

Protection schemes

Optical networks will be used by telecommunications companies and other network providers, which typically require a *carrier grade* reliability.

That is, the network has to be available 99.999% of the time, which translates to an average downtime for the network of 6 minutes per year!

Types of failures:

- Link failures are very common and they occur when a fiber cable is accidentally cut.
- A link can also fail if an amplifier that boosts the multiplexed signal of all the wavelengths on the fiber fails.
- An individual wavelength within a fiber may also fail if its transmitter or receiver fails.
- Finally, an OXC can fail, but this is quite rare due to built-in redundancies.

Path and link protection

Protection can be performed at the level of an individual lightpath or at the level of a single fiber.

- *Path protection* denotes schemes for the restoration of a lightpath, and
- *Link protection* denotes schemes for the restoration of a single fiber, whereby all the wavelengths are restored simultaneously.

Point-to-point links

- The simplest optical network is a point-to-point WDM link that connects two nodes.
- Link protection can be done in a
  - *dedicated 1+1* manner, or in a
  - *non-dedicated 1:1 or 1:N manner*

Dedicated 1+1 scheme:

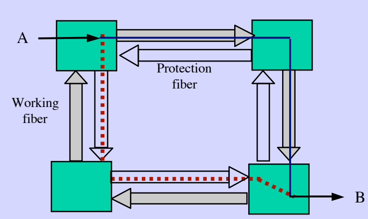
- the signal is transmitted simultaneously over two separate fibers which are preferably diversely routed.
- The receiver monitors the quality of the two signals and selects the best of the two.
- If one fiber fails, then the receiver continues to receive data on the other fiber.

- *1:1 scheme:*
  - There are still two diversely routed fibers, a *working* fiber and a *protection* fiber.
  - The signal is transmitted over the working fiber, and if this fiber fails, the source and destination switch to the protection fiber.
- *Shared 1:N scheme:*
  - This is a generalization of the 1:1 scheme, where N working fibers are protected by a single protection fiber. (Only one working fiber can be protected at any time.)

WDM optical rings

- WDM optical rings can be seen as an extension of the SONET/SDH rings in the WDM domain.
- Many different WDM ring architectures have been proposed. We examine the following rings:
  - *optical unidirectional path sharing ring* (OUPSR),
  - *two-fiber optical bidirectional link sharing ring* (2F-OBLSR)
  - *four-fiber optical bidirectional link sharing ring* (4F-OBLSR).

An optical unidirectional path sharing ring (OUPSR)



- Features
  - It consists of a working and a protection ring transmitting in opposite directions
  - It used as a metro edge ring, and it connects a small number of nodes, such as access networks and customer premises, to a *hub* node, which is attached to a metro core ring.
  - The traffic transmitted on the ring is static and it exhibits hub behavior. That is, it is directed from the nodes to the hub and from the hub to the nodes. Static lightpaths are used.

- Features
  - Transmission is unidirectional.
  - The 1+1 protection scheme is used to implement a simple path protection scheme. That is, a lightpath, is split at the source node and it is transmitted over the working and protection ring.
  - The destination selects the best signal.

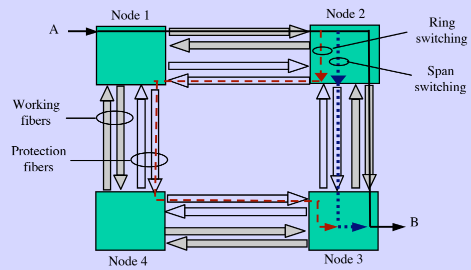
2F-OBLSR and 4F -OBLSR

- The two-fiber and four-fiber optical bidirectional link shared rings are used in the metro core where the traffic patterns dynamically change.
- A signaling protocol is used to establish and tear down lightpaths.
- Protection schemes are implemented using a real-time distributed protection signaling protocol known as the *optical automatic protection switching* (optical APS)

The two-fiber optical bidirectional link shared ring

- It utilizes two rings transmitting in opposite direction as in the OUPSR.
- The wavelengths is each fiber are grouped into two sets: one for working wavelengths and one for protection wavelengths.
- If a fiber fails, the traffic is re-routed onto the protection wavelengths of the other fiber.

The four-fiber optical bidirectional link shared ring



Features

- It utilizes two working fibers and two protection fibers.
- Protection can be done at both the fiber level or at the lightpath level.
- Fiber protection switching is used to restore a network failure caused by a fiber cut or a failure of an optical amplifier. Lightpath protection switching is used to restore a lightpath that failed due to a transmitter or receiver failure.

Span switching

- If the working fiber from node 2 to 3 fails, then all the lightpaths will be switched onto its protection fiber from node 2 to 3.

Ring switching

- If all four fibers are cut between nodes 2 and 3, then the traffic will be diverted to the working fibers in the opposite direction.
- In this case, the lightpath from A to B will be routed back to node 1, and then to node 3 through node 4.

Mesh optical networks

- Both path and link protection can be implemented in a mesh network.
- Link protection can be implemented using the point-to-point 1+1, 1:1, and 1:N schemes
- Path protection is achieved by using dedicated or shared back-up paths.

1+1 path protection

- The user signal is split into two copies and each copy is transmitted simultaneously over two separate diversely routed lightpaths.
- The receiver monitors the quality of the two signals and selects the best of the two. If one lightpath fails, then the receiver continues to receive data on the other lightpath.

1:1 path protection

- In the case of the 1:1 path protection, the user signal is carried over a working lightpath. The back-up protection lightpath has also been established, but it is not used.
- If the working lightpath fails, the source and destination switches to the protection lightpath.

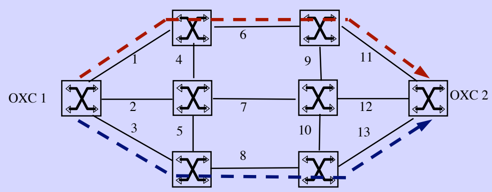
1:N path protection

- This is a generalization of the 1:1 path protection, where N different working lightpaths share the same protection path.
- Obviously, only one working lightpath can be protected at any time

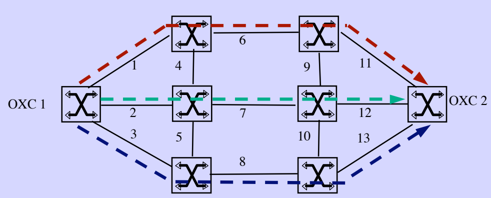
Shared risk link group (SRLG)

- An SRLG is a group of links that share the same physical resource, such as a cable, a conduit, and an OXC.
- Failure of this physical resource will cause failure of all the links.
- When setting up a working and a protection lightpath, care is taken so that the two lightpaths are not routed through the same SRLG.

An example



- The working lightpath from OXC 1 to OXC 2 uses links {1,6,11} and its protection lightpath uses links {3,8,13}.
- That is, they are SRLG-disjoint.



- The concept of SRLG can also be used in the 1:N shared protection scheme.
- The two working lightpaths {1,6,11} and {2,7,12} from OXC 1 to OXC 2 are SRLG-disjoint. Therefore, it makes sense that they both use the same SRLG-disjoint protection lightpath {3,8,13}.

The ITU-T G.709 (The Digital Wrapper)

- Information is typically transmitted over a wavelength using SONET/SDH framing and also Ethernet framing.
- In the future, it will be transmitted using the new ITU-T G.709 standard, otherwise known as the digital wrapper

Features of the G.709 standard

- *Types of traffic:*

  The standard permits the transmission of different types of traffic, such as:
  - IP packets and Gb Ethernet frames using GFP
  - ATM cells
  - SONET/SDH synchronous data.

- *Bit-rate granularity:*

  G.709 provides for three bit-rate granularities: 2.488 Gbps, 9.95 Gbps, and 39.81 Gbps.

  This granularity is coarser than that of SONET/SDH, but is appropriate for terabit networks, since it avoids the large number of sub-rate units.

- *Connection monitoring*:

  Monitoring capabilities permit to monitor a connection on an end-to-end basis over several carriers.

- *Forward error correction (FEC):*

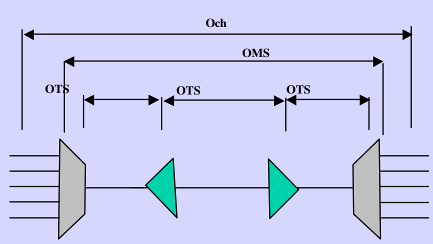
  It is used to detect and correct bit errors caused by physical impairments in the transmission links. (Useful in under-water transoceanic cables, and long-haul links across the continent.)

The optical transport network

In ITU-T, an optical network is referred to as the *optical transport network* (OTN). It consists of three layers:

- *Optical channel* (Och),
- *Optical multiplex section* (OMS),
- *Optical transmission section* (OTS).

The OTN layer structure

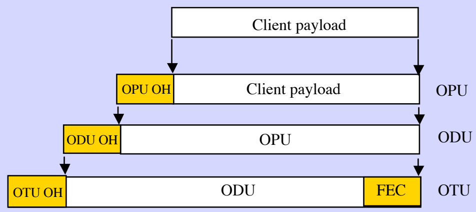


- *Optical channel (Och):* An optical connection between two users that uses an entire lightpath.
- *Optical multiplex section (OMS):* Optical channels are multiplexed and transmitted as a single signal over a fiber. The OMS is the section between a multiplexer and a demultiplexer that carries the combined signal.
- *Optical transmission section (OTS):* This the transport between two access points over which the multiplexed signal is transmitted.

The optical channel (Och) frame

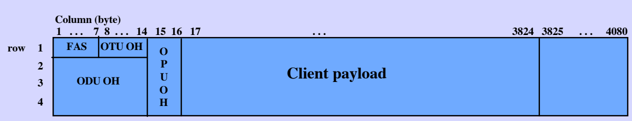
The user data is transmitted in frames which contain several different types of overhead, the user payload, and the forward error correction (FEC).

The optical channel overheads



- *OPU OH (*Och payload unit *):* It includes information related to the client signal (i.e. the type of traffic submitted by the user).
- *ODU OH* (Och data unit*):* It provides tandem connection monitoring, and end-to-end path supervision
- *OTU OH* (Och transport unit): It includes information for monitoring the signal on a section

The format of the OTU frame



- The OUT frame is arranged in a matrix consisting size of 4 rows of 4080 bytes.
- Data is transmitted serially beginning at the top left, first row, followed by the second row, etc

Transmission rates

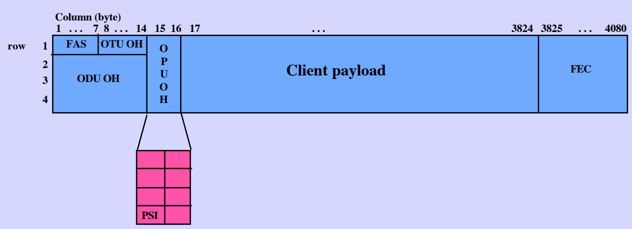
- The following three rates have been defined (including overheads):
  - *2,666,057 Gbps,*
  - *10,709 Gbps,*
  - *43,018,413 Gbps*

- In SONET/SDH, the frame repeats every 125 μsec. Higher rates are achieved by transmitting bigger frames every 125 μsec.

- In G.709 the frame remains the same, but it is transmitted at different rates. The three rates are:
  - Every 48.971 μsec for 2,666,057 Gbps
  - Every 12.191 μsec for 10,709 Gbps
  - Every 3.035 μsec for 43,018,413 Gbps

The OPU overhead

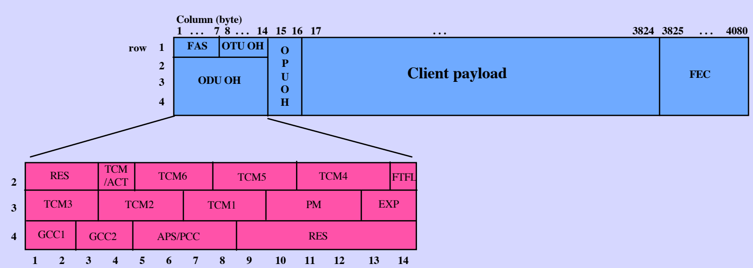
- Located at rows 1 to 4, columns 15 and 16.
- Provides information related to the client signal. It terminates where the client signal is originated and terminated.



- All bytes are reserved except the *payload structure identifier* (PSI). This field transports a 256-byte message aligned with the ODU multi frame.
- The first byte contains the *payload type* (PT) which is used to identify the type of payload carried in the OPU.

The ODU overhead

- Located at rows 2 to 4, columns 1 to 14.
- The ODU OH provides two important overheads: the *path monitoring overhead*, and the *tandem connection monitoring (TCM).*
- The ODU path monitoring OH enables the monitoring of particular sections within the network as well as fault location in the network.
- The tandem connection monitoring enables signal management across multiple networks.



•**RES:** Reserved
•**TCM/ACT**: Activation/deactivation of the TCM fields
•**TCMi**: Tandem Connection Monitoring of ith connection
•**FTFL**: Fault Type & Fault Location reporting channel
•**PM**: Path Monitoring
•**EXP**: Reserved for experimental purposes
•**GCC**: General Communication Channel
•**APS/PCC**: Automatic Protection Switching and protection communication channel

The path monitoring (PM) OH

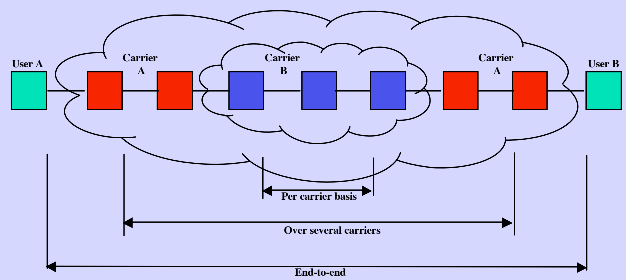
- PM OH occupies columns 10, 11, 12 of row 3.
- The following are some of the defined fields:
  - *Trail trace identifier* (byte 10): It is used to identify the signal from the source to the destination. Similar to the J0 byte in SONET/SDH.
  - *BIP-8* (byte 11): BIP-8 is computed over the whole OPU and it is inserted two frames later.

The tandem connection monitoring (TCM) overhead

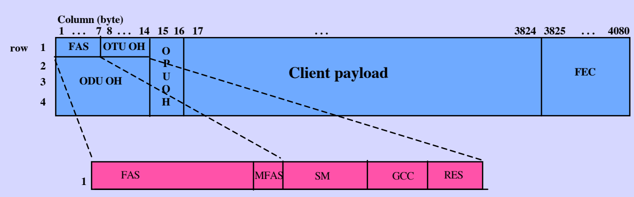
- The TCM OH are defined in row 2, columns 5 to 13, and row 3, columns 1 to 9.
- The TCM functionality implemented in the OTN enables a network operator to monitor the error performance of a connection that originates and terminates within its own network, while it traverses different operators.

An example of network monitoring:

End-to-end, over several carriers, and per carrier basis monitoring can be deployed at the same time



FAS and OUT OH



Frame alignment

- The *frame alignment signa*l (FAS) is carried in the 6-byte frame alignment field
- FAS is used by the receiving equipment to identify the beginning of the ODU frame. The value of FAS is the same as in SONET/SDH: F6F6F6282828, and it is transmitted unscrambled.

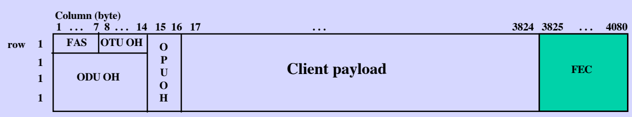
Multi-frame alignment signal

- Some of the OTU and ODU overheads span several OTU frames.
- Because of this, a *multi-frame alignment signal* (MFAS) byte is defined in row 1 column 6.
- The value of MFAS byte is incremented each frame, thereby providing a multiframe consisting of 256 frame.
- It is is transmitted scrambled along with the remaining of the OUT frame

OTU overhead

- Located at row 1, columns 8 to 14.
- Provides supervisory functions for section monitoring and conditions the signal for transport between 3R (re-timing, reshaping, and regeneration) points in the OTN.
- Fields:
  - *SM - section monitoring*
  - *GCC0 - general communication channel*
  - *Reserved for future*

Forward error correction (FEC)



The FEC implementation in G.709 utilizes the Reed-Solomon code RS(255/239).

Client signals

- The following types of traffic can be mapped onto the OPU payload:
  - *SONET/SDH*
  - *IP and Ethernet over GFP*
  - *ATM traffic*
  - *Test signals*

Mapping SONET/SDH into OPU

STS-48, STS-192, and STS-768 data streams are mapped onto an OPU payload using a locally generated clock or a clock derived from the SONET/SDH signal.

Mapping IP and GbE into OPU

This is done using the *Generic Framing Procedure* (GFP), as described in the GFP presentation.

Mapping ATM cells into OPU

- A constant bit rate ATM cell stream with a capacity identical to the OPU payload is mapped by aligning the ATM cell bytes to the OPU bytes.
- Rate coupling maybe necessary.
- A cell may straddle over two successive OPU payloads.
- Cell delineation is derived using the HEC field.

Control plane architectures

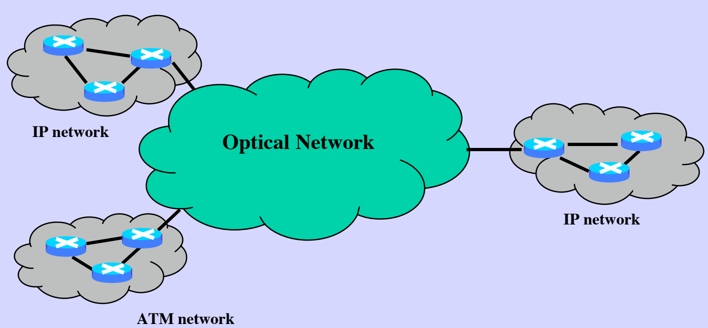
- The control plane consists of protocols that are used to support the data plane, which is concerned with the transmission of data.
- The control plane protocols are concerned with signaling, routing, and networking management.

There are two different control plane architectures:

- In the first control plane architecture:
  - The user is isolated from the network via a user-network interface (UNI)
  - The user is not aware of the network's topology, its control plane, and its data plane.
  - The nodes inside the network interact with each other via a network-node interface (NNI).
  - ATM is a good example of this architecture

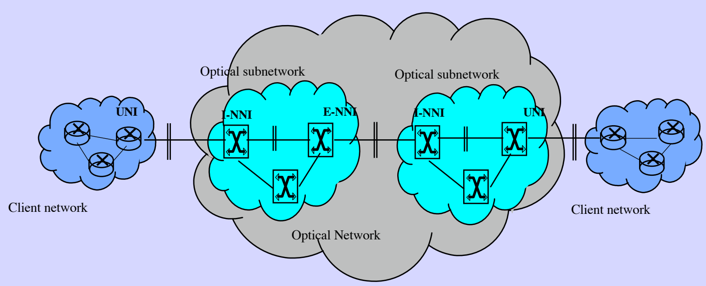
In the second control plane architecture:

- The user is not isolated from the network through a UNI
- The nodes inside the network do not interact with each other via a separate NNI.
- All users and nodes run the same set of protocols
- The IP network is a good example of this architecture



An optical network provides inter-connectivity to client networks, such as IP, Frame Relay, ATM and SONET/SDH

- A large optical network will typically consist of interconnected smaller optical sub-networks, each representing a separate *control domain*.
- Each of these smaller networks could be a different administrative system.
- Also, the equipment within a smaller network could all be of the same vendor, with their own administrative and control procedures.



- Interfaces defined in the first control plane architecture:
  - User-network interface (UNI)
  - Internal network-node interface (I-NNI)
  - External network-node interface (E-NNI)

The OIF UNI

- OIF has specified a UNI which provides signaling for clients to automatically create a connection.
- The UNI is based on LDP and RSVP-TE protocols

IETF control plane architectures

- IETF has defined the following three control plane architectures:
  - Peer model
  - Overlay model
  - Augmented model

The peer model

- The peer model utilizes the second control plane architecture.
- That is, the client networks and the optical networks are treated as a single network from the point of view of the control plane.
- The generalized MPLS (GMPLS), an extension of MPLS, is used in the control plane.

Routing in the peer model

- The IP and optical networks run the same IP routing protocol, i.e OSPF with suitable "optical" extensions.
- The topology and link state information maintained by all nodes (OXCs and routers) is identical.
- A router can compute an LSP end-to-end.
- An LSP can be established using CR-LDP extended for GMPLS or RSVP-TE extended for GMPLS.

The overlay model

- This model utilizes the first control plane architecture.
- An IP client network is connected to the optical network via an edge IP router which has an optical interface to its ingress optical node, i.e. the optical node to which it is directly attached.
- An edge IP router has to request the establishment of a connection from its ingress optical node, before it can transmit over the optical network. This is done using a signaling protocol.

- A connection over the optical network may be a permanent or a switched lightpath or sub-channel.
- The edge router is not aware of the topology of the optical network nor is it aware of its control and data planes.
- The control plane of the optical network may be based on GMPLS. However, a strict separation of the client networks and the optical network is maintained through the UNI.

The augmented model

- The IP and optical networks use separate control planes.
- However, information from one routing protocol is passed to the other.
- For instance IP addresses from one IP network can be carried by the optical network to another IP network to allow reachability.

Generalized Multi-Protocol Label Switching (GMPLS)

- GMPLS is an extension of MPLS.
- MPLS was designed originally to introduce label-switched paths into the packet-switched network
- GMPLS was designed with a view to applying label-switching techniques to time-division multiplexing (TDM) networks and wavelength routing networks in addition to packet-switching networks.

- GMPLS, like MPLS, can be used to setup an LSP through an IP network and other packet-switched networks.
- It can also be used to:
  - setup a circuit-switched connection in a SONET/SDH network.
  - setup a lightpath in a wavelength routing optical network.

- In GMPLS
  - IP routers, ATM switches, Frame Relay switches, Ethernet switches, DCSs and OXCs

  are all treated as a single IP network from the control point of view.
- There are no UNIs and NNIs, since GMPLS is a peer-to-peer protocol.

GMPLS interfaces

- A GMPLS-capable LSR may support the following interfaces:
  - *Packet-switch capable (PSC) interfaces*
  - *Time-division multiplex capable (TDM) interfaces*
  - *Lamda switch capable (LSC) interfaces*
  - *Fiber-switch capable (FSC) interfaces*

- *Packet-switch capable (PSC) interfaces*:
  - These are the different interfaces used to receive and transmit packets, such as IP packets, ATM cells, Frame Relay frames, and Ethernet frames. Forwarding of these packets is based on an encapsulated label, VPI/VCI field, DLCI field.
- *Time-division multiplex capable (TDM) interfaces:*
  - They forward data based on the data's slot(s) within a frame. This interface is used in a SONET/SDH DCS.

- *Lamda Switch Capable (LSC) interfaces*
  - They forward data from an incoming wavelength to an outgoing wavelength. This interface is used in OXCs.
- *Fiber-switch capable (FSC) interfaces*
  - They forward data from one (or more) incoming fibers to one (or more) outgoing fibers. They are used in an OXC that can operate at the level of one (or more) fibers.

A hierarchy of interfaces

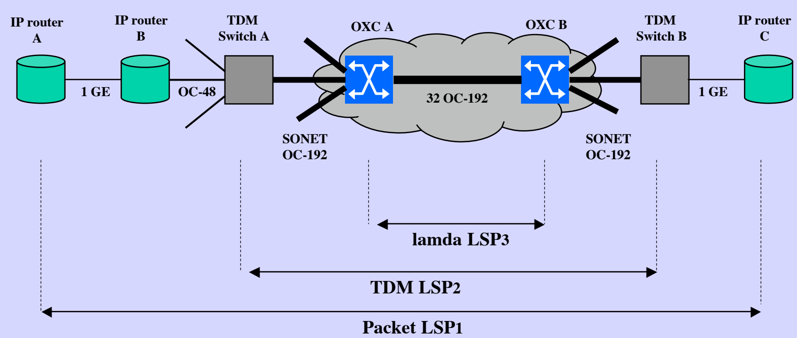
- These four interfaces form a hierarchy used to support hierarchical LSPs

PSC — **Highest level**
TDM
LSC
FSC — **Lowest level**

Hierarchical LSPs

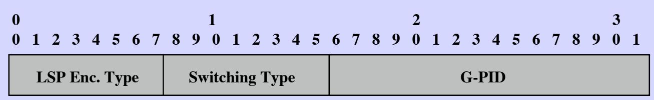
- An LSP may start and end at a packet-switched interface (PSC) .
- It can be then nested together with other LSPs within an LSP that starts and ends on a TDM interface, which in turn is nested (together with other) within an LSP that starts and ends on a lamda switched interface (LSC).

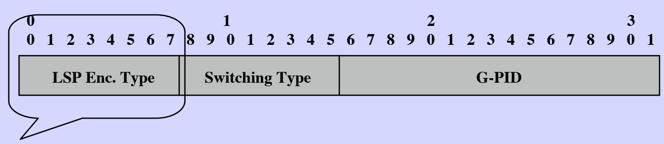
An example of a hierarchical LSP



The generalized label request

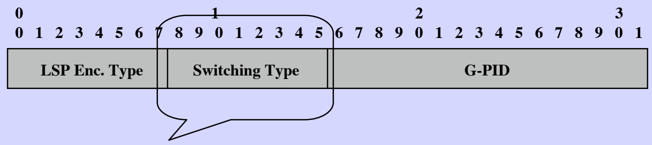
- The generalized label request is used to request the establishment of an LSP.
- The following information is carried:



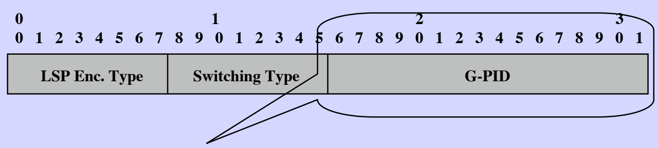


- *LSP Encoding Type* (8 bits): It indicates how the data to be transmitted over the LSP will be encoded. The following values have been defined.

Value	Type
1	Packet
2	Ethernet V2/DIX
3	ANSI PDH
4	ETSI PDH
5	SDH ITU-T G.707
6	SONET ANSI T1.105
7	Digital wrapper
8	lamda (photonic)
9	Fiber
10	Ethernet 802.3
11	Fiber Channel



- *Switching Type* (8 bits):
  - It indicates the type of switching that should be performed on a particular link.
  - This field is needed on links that advertise more than one type of switching capability



- *Generalized payload identifier (G-PID) -* 16 bits: It used to identify the payload carried by an LSP. It is used by the endpoints of the LSP. Some of the values are:

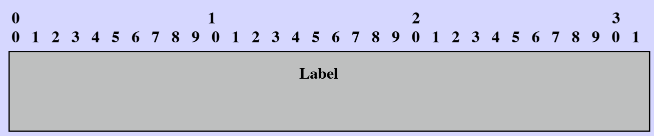
Value	Type	Technology
0	Unknown	All
14	Byte synchronous mapping of E1	SDH
17	Bit synchronous mapping of DS1/T1	SDH
28	POS- No scrambling, 16 bit CRC	SONET
32	ATM mapping	SONET, SDH
33	Ethernet	Lamda, Fiber
34	SDH	Lamda, Fiber
35	SONET	Lamda, Fiber
36	Digital wrapper	Lamda, Fiber
37	Lamda	Fiber

The generalized label

- Several new forms of labels are required to deal with the widened scope of MPLS into the optical and time-division multiplexing domains.
- The generalized label not only allows for the familiar MPLS-type label that travels in-band with the associated packet, but also it allows for labels which identify time-slots, wavelengths, or fibers.

- The generalized label may carry a label that represents:
  - *Generic MPLS label Frame Relay label, ATM label*
  - *A set of time-slots within a wavelength, or fiber*
  - *A single wavelength within a waveband, or fiber*
  - *A single waveband within a fiber*
  - *A single fiber in a bundle*
- These new forms of labels are collectively referred to as the *generalized label*.

- Since the node using GMPLS knows the type of link used, the generalized label does not contain a type field.
- The generalized label is not hierarchical. When multiple level of labels are required, each LSP must be established separately.
- Format:



The suggested label

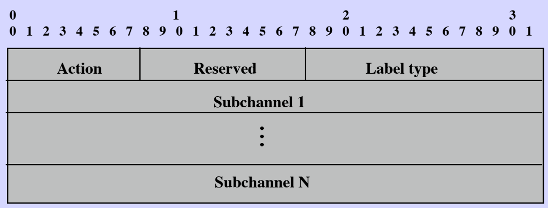
- This is used to provide a downstream node with the upstream node's label preference.
- This permits the upstream node to start configuring its hardware with the proposed label before the label is communicated by the downstream node. (Useful, if time to configure a label is non-trivial).
- It can be over-ridden by the downstream node.
- Suggested label format: Same as generalized label

The label set

- The label set is used to limit the label choice of a downstream node to a set of acceptable labels.
- The receiver must restrict its choice of labels to one which is in the label set.

- There are four cases where a label set is useful in the optical domain:
  - *Case 1:* The end equipment is only capable of transmitting/receiving on a small specific set of wavelengths
  - *Case 2:* There is a sequence of interfaces which cannot support wavelength conversion, and require the same wavelength to be used over a sequence of hops, or even the entire path.
  - *Case 3:* Limit the number of wavelength conversion along the path.
  - *Case 4:* Two ends of a link support different sets of wavelengths

- A label set is composed of *one or more elements.*
- Each element is referred to as a *subchannel identifier* and it has the same format as a generalized label.
- The information carried in a label set is:



- *Action:* This 8-bit field indicates how the label set is to be interpreted. The following values have been defined:
  - *Inclusive list (value set to 0)*
  - *Exclusive list (value set to 1)*
  - *Inclusive range (value set to 2*
  - *Exclusive range (value set to 3)*
- *Label type:* A 14-bit field used to indicate the type and format of the labels carried in the object/TLV.

Bi-directional LSPs

- In MPLS two unidirectional LSPs have to be established in order to provide bi-directional connectivity.
  - Double latency
  - Twice control overhead
  - Route selection may be complicated
- In GMPLS, bi-directional optical LSPs can be set-up

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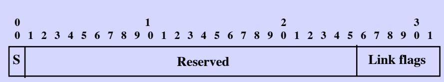
Protection information

- It is used to indicate the required protection desired for the LSP., i.e., dedicated 1+1, dedicated 1:1, shared 1:N, unprotected.
- Protection information also indicates if the LSP is a primary or a secondary LSP.



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- *Secondary (S):* A 1-bit field used to indicate that the requested LSP is a secondary LSP
- *Link flags:* It indicates the desired protection type:
  - *Enhanced:* A protection scheme which is more reliable than dedicated 1+1 should be used, i.e., 4 fiber BLSR.
  - *Dedicated 1+1*
  - *Dedicated 1:1.*
  - *Shared* (1:N)
  - *Unprotected*
  - *Extra traffic:* It indicates that the requested LSP should use links that are protecting other primary LSPs.

Protocols for GMPLS

- GMPLS is an architecture, and as in MPLS, it requires a signaling protocol for the reliable distribution of label bindings.
- Both CR-LDP and RSVP-TE have been extended to support GMPLS. The extensions are presented below.
- IS-IS and OSPF have also been extended to support GMPLS.

CR-LDP extensions for GMPLS

New TLVs have been introduced in CR-LDP to support GMPLS. Specifically,

- *The generalized label request TLV*
- *The generalized label TLV*
- *The suggested label TLV*
- *The label set TLV*

U	F	Type		length	
LSP enc. type			Switching type	G-PID	

The CR-LDP generalized label request TLV

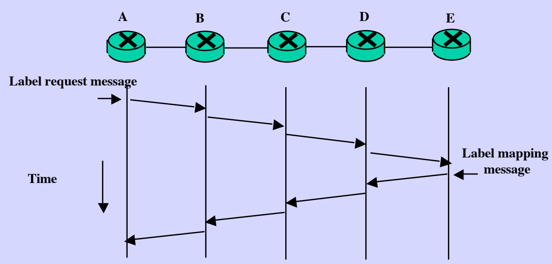
U	F	Type	length
Label			

The CR-LDP generalized label TLV

U	F	Type		length	
Action			Reserved	Label type	
Sub-channel 1					
…					
Sub-channel N					

The CR-LDP label set TLV

The establishment of a CR-LDP



Bidirectional LSPs

- They are set-up using the same process of establishing a unidirectional LSP with an upstream label added to the label request message.
- A receiving node provides a new upstream label and then forwards the request message to the next downstream node.
- As the request message propagates towards the destination LSR E, labels for the path from LSR E to LSR A are being setup.
- The labels for the path from LSR A to LSR E are setup as the mapping message propagates towards LSR A.

RSVP-TE extension for GMPLS

- As in the case of CR-LDP, new objects have been introduced in RSVP-TE to support the generalized label operation.
  - *The generalized label request object*
  - *the generalized label object*
  - *the suggested label object*
  - *the label set object*

0 1 2 3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1

Length		**Class-Num**	**C-type**
LSP enc. type	**Switching type**	**G-PID**	

The RSVP-TE generalized label request object

0 1 2 3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1

Length	**Class-Num**	**C-type**
Label		

The RSVP-TE generalized label object

0 1 2 3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1

Length	**Class-Num**	**C-type**
Action	**Reserved**	**Label type**
Sub-channel 1		
...		
Sub-channel N		

The RSVP-TE label set object

Bidirectional LSPs

- They are setup using the same process of establishing a unidirectional LSP with some additions.
- An upstream label is added to the Path message, which permits the allocation of labels along the path from the destination LSR to the source LSR.
- Labels along the path from the destination LSR to the source LSR are allocated as in the unidirectional LSP using the Resv message.

The OIF UNI 1.0

- OIF-UNI specifies signaling procedures for clients to automatically create, delete, and query the status of a connection over an optical network.
- The UNI is based on the GMPLS signaling protocols: LDP and RSVP-TE.
- Also it uses extensions of Link Management Protocol (LMP)

- Client:
  - This is network equipment connected to the transport network, such as IP routers, ATM switches, SONET/SDH cross connect
- UNI-C and UNI-N
  - UNI-C is the UNI interface at the client's side
  - UNI-N is the UNI interface at the network's side

The UNI data plane

- The link between the client and its ingress node, known as *terminal network element* (TNE), is SONET/SDH.
- The transmission rate can be up to STS-76.

IPCC

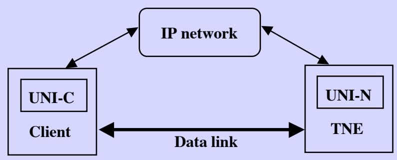
- UNI signaling messages are transported in IP packets between the UNI-C and UNI-N.
- The UNI defines an *IP control channel* (IPCC) for this purpose.
- This channel may be
  - *in-fiber* or
  - *out-of-fiber*.

In-fiber IPCC

- The signaling messages are carried over a common channel embedded in the data-carrying optical link between the client and the TNE.
- For this, the user can use the line and section overhead D bytes in the SONET frame.

Out-of-fiber IPCC

- The signaling messages are carried over a dedicated communication link, which is separate from the link that is used to transmit the data.
- Such a link can be over a Ethernet or an IP network.



Addressing - TNA

- The topology, resources, and addressing of the optical network is not revealed to the clients.
- A *transport network administrative* (TNA) address is used by the UNI to identify a client.
- The TNA address is a globally uniquely defined address and distinct from the native address spaces of both the clients and the network.

- To maintain compatibility with network devices that use different addressing types, the TNA may be in the form of IPv4, IPv6, and NSAP.
  - IPv4 uses a 32 bit address
  - IPv6 uses a 128 bit address
  - NSAP uses 160 bits (see ATM book)
- The UNI allows a connection between two different TNA type address

Services offered over the UNI

- The primary services offered to a client by the transport network over the UNI is the ability to create and delete connections on demand.
- Also, the following optional procedures are specified:
  - Neighbor discovery
  - Service discovery

The UNI abstract messages

- A number of abstract signaling messages have been defined. The actual implementation depends on whether CR-LDP or RSVP-TE is used.
- These messages are used to create, delete, and query the status of connections established over the UNI.

- From the UNI point of view, a connection is a circuit with fixed-size bandwidth between an ingress and an egress optical node with a specified frame.
- At this moment only SONET/SDH framing is used.
- A connection could be unidirectional or bi-directional.

Abstract messages

- *Connection create request*
- *Connection create response*
- *Connection create confirmation*
- *Connection delete request*
- *Connection delete response*
- *Connection status enquiry*
- *Connection status response*
- *Notification*

Connection create request

- This message is sent by the UNI-C to UNI-N to request the creation of a connection.
- The egress UNI-N sends the message to the destination UNI-C to indicate an incoming connection request.

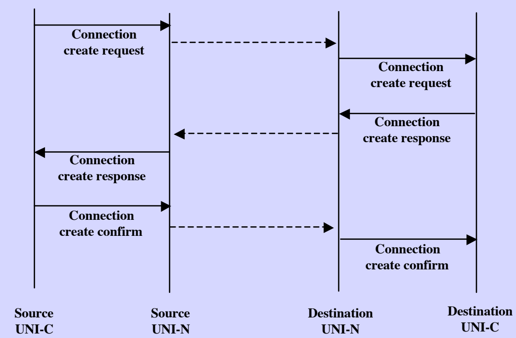
Connection create response

- This message is used to acknowledge establishment of the connection to the UNI-C that initiated the connection request.
- It is sent from the destination UNI-C to destination UNI-N, and from the ingress UNI-N to the UNI-C that initiated the connection request.
- The UNI-C client can start transmission upon receipt of this message.

Connection create confirmation

- This message is used from the initiating UNI-C to its ingress UNI-N to acknowledge completion of the connection establishment.
- The destination UNI-N to destination UNI-C to indicate that the connection has been successfully established.

Connection establishment



Connection delete request/response

- The connection delete request message is used to initiate the deletion of a connection, and it can be sent by either UNI-C.
- It can also be sent by the network in case of internal network failure.
- The connection delete response message is used to signal the completion of the deletion of a connection procedure.

Connection status enquiry/response

- The connection status enquiry message is used to query the status and attributes of a given connection.
- The connection status response is used to return the status of the specified connection and its attributes.

Notification

- It is used by a UNI-N to either UNI-C to indicate a change in the status of the connection.

Attributes

- Each abstract message has a number of mandatory and optional attributes. These are organized logically into the following groups:
  - *Identification-related attributes*
  - *Service-related attributes*
  - *Routing-related attributes*
  - *Policy-related attributes*
  - *Miscellaneous attributes*

Identification-related attributes

Some of these attributes are:

- TNA address
  - Source and destination TNA addresses
- Logical port identifier
  - It indicates the client or TNE port number used for the connection
- Local connection ID
  - An identifier with local significance, assigned by the UNI-C that initiates the connection. It is used in all messages to identify which connections the messages apply to.

Service-related attributes

Some of the attributes are:

- Encoding type:SONET or SDH.
- SONET/SDH traffic parameters
  - Signal type and concatenation.
- Directionality
  - It indicates unidirectional or bi-directional connection
- Generalized payload identifier
  - It indicates the payload carried within the established connection.

- Service level
  - It indicates a class of service. Since the optical network is circuit-switched, the class of service is not the typical one we encounter in packet-switching, i.e. packet loss and end-to-end delay.
  - The class of service is related to issues such as the restoration scheme, i.e. no restoration, 1+1 protection, etc), and the connection set-up and hold priorities

Routing-related attributes

The only attributes defined is:

- Diversity
  - This attribute specifies at what level a new connection must be diversely routed from existing connections which start at the same TNE. A new connection maybe disjoint from an existing connections. It can also be routed identically to an existing connection.

Some of the attributes for the connection create request

- Source TNA (M)
- Source logical port identifier (M)
- Destination TNA address (M)
- Destination logical port identifier (O)
- Local connection ID (M)
- Encoding type (M)
- SONET/SDH traffic parameters (M)
- Directionality (O)
- Generalized payload identifier (O)

LDP extensions for UNI signaling

- Two main guiding principles were used when extending LDP for UNI signaling :
  - Limit the introduction of new LDP messages.
    - Only two new messages were introduced to support the status enquiry messages.
  - LDP extensions should be easily implemented as simple addition to the existing LDP implementation, without violating the LDP semantics.

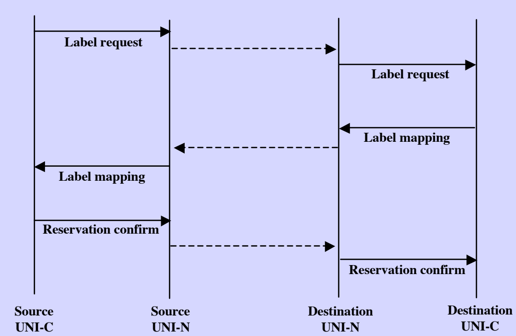
LDP session initialization

- A single LDP session between the UNI-C and the UNI-N is established, regardless of the number of data links between the client and the TNE.
- LDP hello and extended hello are used for neighbor discovery

Connection create using LDP

- The connection create request is implemented in LDP signaling using the label request msg.
- This is sent from the source UNI-C to the source UNI-N, and from the destination UNI-N to destination UNI-C.
- The label request message was extended to support the signaling of the UNI attributes

Connection establishment using LDP



Connection deletion

- LDP employs two mechanisms for an LSR to inform its peer to stop using a particular label:
  - label withdraw message and
  - label release message.

Failure detection and recovery

- The LDP keepAlive message is used to detect signaling communication failures between a UNI-C and a UNI-N.

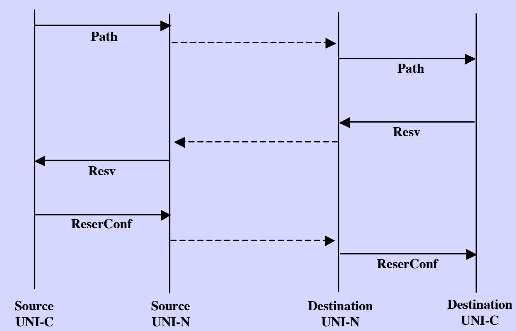
RSVP extensions for UNI signaling

- Most of the UNI abstract messages are directly supported by reusing existing procedures, messages, and objects defined in RSVP-TE and GMPLS extensions for RSVP-TE.
- There is no implied requirement that RSVP-based signaling be supported within the network.

Connection establishment

- UNI-C sends a Path message to its UNI-N.
- The Path message includes a GENERALIZED_LABEL_REQUEST object, which indicates that a label binding is requested.
- The traffic parameters of the connection are encoded in a SONET/SDH SENDER_TSPEC object in the Path message and a SONET/SDH FLOWSPEC object in the corresponding Resv message.

Connection establishment in RSVP



Connection deletion

- A connection in RSVP can be deleted either using a single PathTear messageor a ResvTear message and PathTear message combination.
- The deletion of a connection may cause the optical network to think that the connection has failed, which may lead to management alarms. For this reason, a graceful connection deletion procedure is followed.