The Migration Toward the Optical Internet

Lesson 8

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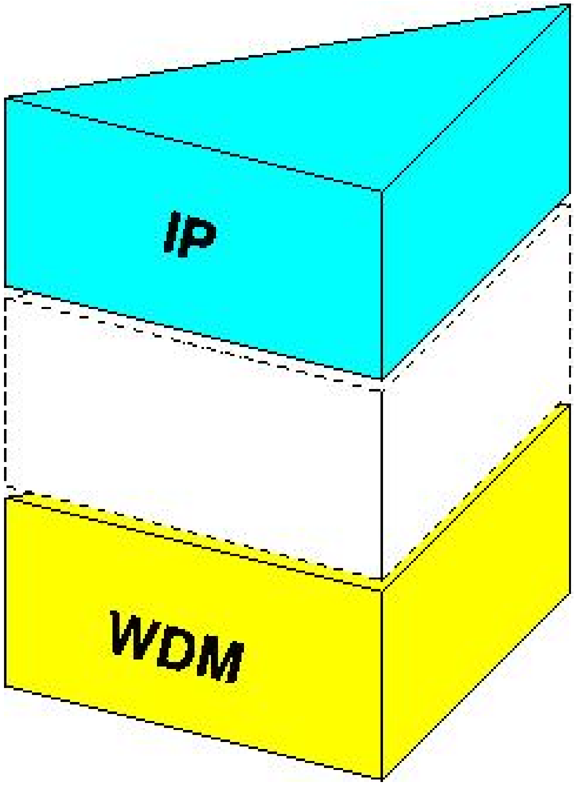
IP over Optical Layer (WDM)

- Advantages
  - WDM ⇒ high bandwidth availability (> 10THz)
  - IP/WDM ⇒ elimination intermediate layers redundancies (IP/ATM/SONET/WDM)
- Drawbacks
  - IP and WDM layer coordination
  - Missing resilient transport layer (e.g., SONET/SDH)

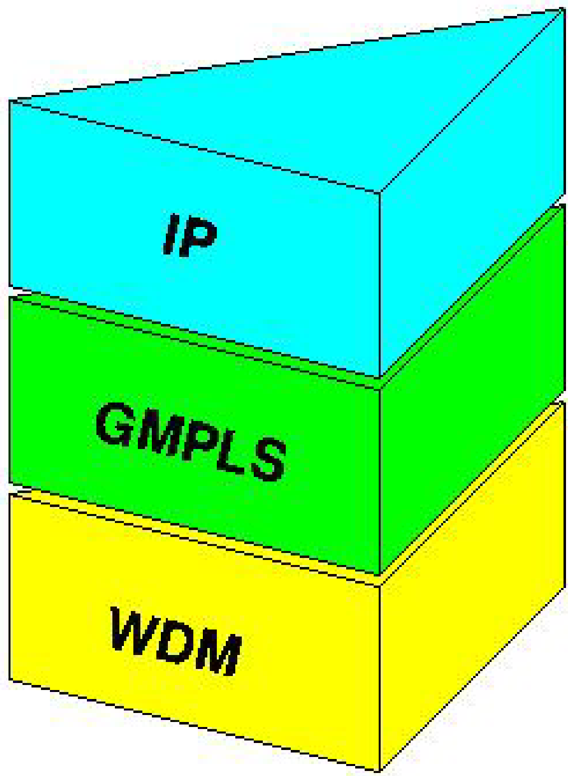


IP over WDM Coordination

- Overlay model
  - IP client
  - WDM server
  - Separated IP and WDM control planes
  - User to Network Interface (UNI) between IP and WDM
- Peer model
  - Integrated control plane (Generalized MultiProtocol Label Switching - GMPLS)

GMPLS Enabled Intelligent Optical Network Architecture

- IP over WDM
- IP/GMPLS control plane
  - Routing ⇒ IGP (e.g., OSPF, OSPF-TE)
  - Signaling ⇒ GMPLS (e.g., CR-LDP, RSVP-TE)
- WDM data plane
- Highly dynamic IP traffic characteristics ⇒ high flexibility in WDM



Generalized Multiprotocol Label Switching (GMPLS)

- Extends MPLS to provide the control plane (routing and signaling) for devices that switch in any of these domains
  - packet
  - time
  - wavelength
  - fiber
- The common control plane promisesto simplify network operation and management by
  - automating end-to-end provisioning of connections
  - managing network resources
  - providing the level of QoS that applications expect

GMPLS Impact

- GMPLS provides the ability to automate network resource management and service provisioning of end-to-end traffic engineered paths
- Deployment of GMPLS-based nodes allow carriers to
  - avoid manual, lengthy, and costly manual provisioning of traditional SONET/SDH-based networks
  - automate the provisioning and management of the network
    - This could lower the cost of operation by several orders of magnitude (days or even minutes instead of week or months)

Evolution of GMPLS from MPLS

- Current IP-based MPLS networks are capable of providing advanced services such as
  - bandwidth-based guaranteed service
  - priority-based bandwidth allocation
  - preemption services
- MPLS place IP traffic on a defined engineered path, i.e., Label Switched Path (LSP)

MPLS Signaling

- Signaling to establish a traffic-engineered LSP is done using a label distribution protocol that runs on every MPLS node
- Different label distribution protocols
  - Resource reSerVation Protocol-traffic engineering (RSVP-TE)
    - Extended version of the original RSVP used in IP
  - Constraint-Based Label Distribution Protocol (CR-LDP)
    - Designed specifically for the purpose of piggyback and distribute label on its messages and to provide traffic-engineering capabilities

MPLS Routing

- Extension to existing IP link-state routing protocols
- Routing protocols provide real-time coordination of the current network topology, including attributes of each link
- MPLS extensions to OSPF and Intermediate System-Intermediate System (IS-IS) allow node to exchange extended information
  - (not only) network topology configuration
  - resource information and policy information
    - IP addresses
    - available bandwidth
    - load-balancing policies
- Constraint-based routing algorithms use this information to compute the optimal paths for the LSPs through the network

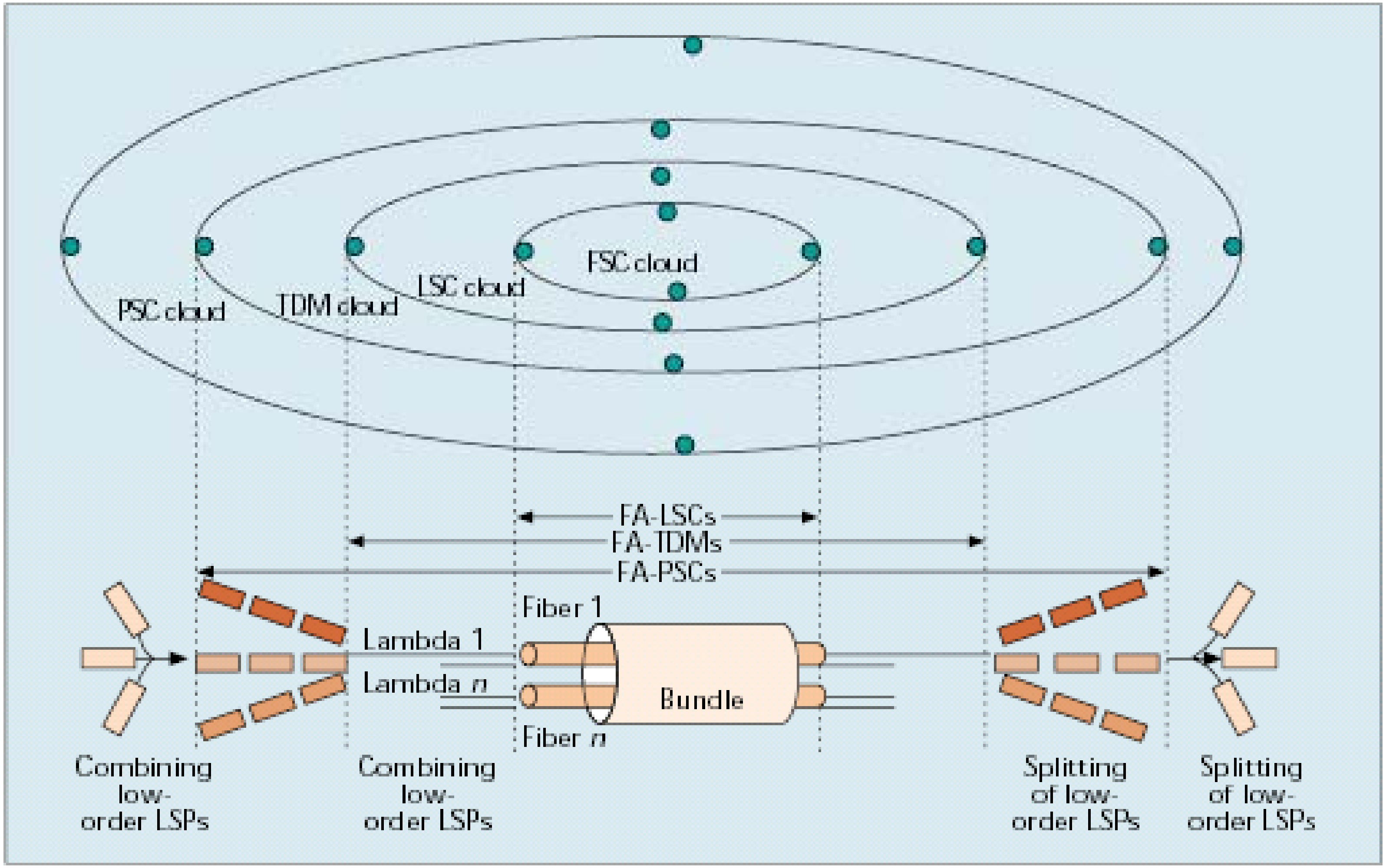
MPLS Evolution to GMPLS

- MPLS suite of protocols has been extended to include devices that switch in
  - time
  - wavelength (e.g., DWDM)
  - space (e.g., Optical Crossconnect OXC)
- The extended MPLS is named Generalized MPLS (GMPLS)
- GMPLS-based networks are able to find and provision an optimal path based on user traffic requirements for a flow that potentially starts on an IP network, is then transported by SONET, and then is switched through a specific wavelength on a specific physical fiber

Switching Domains

Switching Domain	Traffic Type	Forwarding Scheme	Example of Device	Name
Packet, cell	IP, ATM	Label as shim header, virtual cannel connection (VCC)	IP router, ATM switch	Packet Switch Capable (PSC)
Time	TDM/SONET	Time slot in repeating cycle	Digital cross-connect system (DCS), ADM	TDM capable
Wavelength	Transparent	Wavelength	DWDM	Lambda switch capable (LSC)
Physical space	Transparent	Fiber, line	OXC	Fiber switch capable (FSC)

GMPLS Domain



Required Modifications to MPLS

- New Link Management Protocol (LMP) to address issues related to link management in optical networks using photonic switches
- Enhancements to OSPF/IS-IS routing protocols to advertise availability of optical resources in the network (e.g., generalized representation of various link types, bandwidth on wavelengths, link protection type, fiber identifiers)
- Enhancements to the RSVP/CR-LDP signaling protocols for traffic engineering purposes that allow a label-switched path (LSP) to be explicitly specified across the optical core
- Scalability enhancements such as hierarchical LSP formation, link bundling, and unnumbered links

Enhancements to Routing

- MPLS label space is comparatively large (one million per port)
  - there are a relatively limited number of lambdas and TDM channels (tens to hundreds per port today, scaling to thousands over the next few years)
- MPLS LSPs can be allocated bandwidth from a continuous spectrum
  - Optical/TDM bandwidth allocation is from a small discrete set of values
- To handle the growth of traffic providers need to deploy hundreds of parallel fibers, each carrying hundreds of lambdas between a pair of network elements ⇒sub-issues
  - The overall number of links in an optical/TDM network can be several orders of magnitude larger than that of an MPLS network
  - Assigning IP addresses to each fiber, lambda, and TDM channel is a serious concern, because of both the scarcity of IP addresses and the management burden
  - Identifying which port on a network element is connected to which port on a neighboring network element is a major management burden and highly error prone

Enhancement to Routing (2)

- Fast fault detection and isolation, and fast failover to an alternate channel are needed
- The user data carried in the optical domain is transparently switched to increase the efficiency of the network. This necessitates transmitting control plane information decoupled fromuser data

Enhancements to Signaling

- Enhancements to signaling (RSVP-TE and CR-LDP) allow the signaling and instantiation of optical channel trails in optical transport networks and other connection-oriented networking environment
- In order to set up LSPs between transparent devices, signaling requests need to be terminated $\Rightarrow$ separate control plane transport network to convey signaling messages
- GMPLS allows the control plane to be physically diverse from the associated data plane

Enhancements to Signaling (2)

- Hierarchical LSP Setup
  - GMPLS supports the concept of Hierachical LSP
  - Hierarchical LSP is when a new LSP is tunneled inside an existing higher-order LSP so that the preexisting LSP services as a link along the path of the new LSP

Enhancements to Signaling (3)

- Suggested Label
  - GMPLS signaling allows a label to be suggested by an upstream node
  - The suggested label is particularly valuable
    - when it is desired to set up a bidirectional LSP during paired transmit (Tx) and receive (Rx) interfaces to the same physical port (e.g., WDM transponders Tx/Rx pair)
    - to set up an LSP transiting certain kinds of optical switching equipment where there is some latency associated with configuring the switching fabric
    - in optical subnetworks with limited wavelength conversion capability where wavelength assignment can be performed by the originating node of an optical LSP to minimize blocking probability

Enhancements to Signaling (4)

- Bidirectional optical LSPs (lightpaths)
  - it is assumed that both directions of such LSPs have the same traffic engineering requirements, including fate sharing, protection, and restoration, and resource requirements
  - initiator = node that starts the establishment of and LSP
  - terminator = LSP destination node
  - In the basic MPLS architecture LSPs are unidirectional so in order to establish a bidirectional LSP two unidirectional LSPs in opposite directions must be established independently
  - Additional methods have been defined to allow bidirectional LSP’s downstream and upstream data paths to be established using a single set of Path/Request and Resv/Mapping messages

Enhancements to Signaling (5)

- Key requirements for providing network reliability
  - quick reaction to failures
  - decisions made intelligently
- Notify message has been added to RSVP-TE for GMPLS to provide a mechanism for informing nonadjacent nodes of LSP-related failures
  - similar mechanism has not been defined for CR-LDP
- The Notify message does not replace existing RSVP error messages
- it differs from them in that it can be targeted to any node other than the immediate upstream or down stream neighbor

Introduction to Mathematical Programming

- Def. Decision variables
  - variables whose values are to be decided in some optimal fashion
  - x_j, j=1, 2, …, n
- Def. Objective function
  - a combination of coefficients and decision variables (mathematical programming)
  - $Z=f(x_1, x_2, \ldots, x_n)$
  - a linear combination of the decision variables (linear programming)
  - $Z=c_1 x_1 + c_2 x_2 + \ldots + c_n x_n$

Introduction to Mathematical Programming (2)

- Def. Constraints
  - equalities and inequalities with combination of the decision variables that limit the values the decision variables can take (mathematical programming)
  - equalities and inequalities with linear combination of the decision variables (linear programming)

$$a_1 x_1 + a_2 x_2 + \ldots + a_n x_n \begin{Bmatrix} \leq \\ = \\ \geq \end{Bmatrix} b$$

Introduction to Mathematical Programming (3)

- The objective of a mathematical program is usually to minimize or maximize the objective function
  - To convert a maximization to a minimization is sufficient to change the sign of the objective function
  - Max Z= Min -Z
- Def. Solution
  - A proposal of specific values for the decision variables
- Def. Feasible Solution
  - A solution (x_1, x_2, …, x_n) is called feasible if it satisfies all of the constraints
- Def. Feasible Solution Space
  - collection of all the solutions that satisfies the limitation imposed by the constraints
- Def. Optimal Solution
  - the feasible solution that maximizes or minimizes the objective function
- Def. Globally Optimal Solution
  - it is an optimal solution with respect to the entire feasible solution space
- Def. Locally Optimal Solution
  - it is an optimal solution with respect to only a limited portion of the feasible solution space

Introduction to Mathematical Programming (4)

- Mathematical programs can often be solved with algorithms
- Def. Algorithm
  - solution procedure that consists of a number of understandable steps and can be implemented on a computer
- Some algorithms for some problems are exact and will be guaranteed to always produce a globally optimal solution
- Sometimes an algorithm to produce a globally optimal solution is not known
- Def. Heuristic algorithms
  - algorithms that use intuitive procedures to develop solutions that may be close to being optimal (i.e., sub-optimal solutions)

Linear Programming

- Def. Linear Program
  - a mathematical program in which both the objective function and and the constraint equations are linear function of the decision variables
- Nonlinear Programming deals with the solution of nonlinear models

Linear Programming Standard (Canonical) Form

- All inequalities are less-thans
- All decision variables are non-negative

Objective function

$$\max Z = c_1 x_1 + c_2 x_2 + \ldots + c_n x_n$$

Subject to (Constraints)

$$a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \le b_1$$

$$a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n \le b_2$$

$$\vdots$$

$$a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n \le b_m$$

$$x_1, x_2, \ldots, x_n \ge 0$$

Linear Programming
Matrix Representation

$$\min Z = \mathbf{c}^{\mathrm{T}}\mathbf{x}$$

$$\mathbf{A}\mathbf{x} = \mathbf{b}$$

$$\mathbf{x} \geq \mathbf{0}$$

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}$$

$$\mathbf{c} = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{bmatrix} \qquad \mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \qquad \mathbf{b} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix}$$

Constraint Conversion

- Conversion of an inequality constraint to an equality constraint
- Introduction of a *slack variable*

$$a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n \leq b_i$$

$$\Downarrow$$

$$a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n + w_i = b_i$$

$$w \geq 0$$

Constraint Conversion (2)

- Conversion of an inequality constraint to an equality constraint
- Introduction of a *surplus variable*

$$a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n \geq b_i$$

$$\Downarrow$$

$$a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n - y_i = b_i$$

$$y_i \geq 0$$

Constraint Conversion (3)

- Conversion of an equality constraint to two inequality constraints

$$a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n = b_i$$

$$\Downarrow$$

$$a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n \leq b_i$$
$$a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n \geq b_i$$

Linear Programming Examples

- Infeasible problem
  - If a problem has no feasible solution is called infeasible
  - the second constraint implies that $x_1+x_2 \geq 4.5$ which contradicts the first constraint

$$
\begin{aligned}
&\max 5x_1 + 4x_2 \\
&s.t. \\
&x_1 + x_2 \leq 2 \\
&-2x_1 - 2x_2 \leq -9 \\
&x_1, x_2 \geq 0
\end{aligned}
$$

Linear Programming Examples (2)

- Unbounded problem
  - A problem is unbounded if it has feasible solutions with arbitrarily large objective values
  - if x_2 is set to zero and x_1 is let be be arbitrarily large as long as $x_1>2$
    - the solution is feasible
    - and the objective function gets large too

$$\max x_1 - 4x_2$$

$$s.t.$$

$$-2x_1 + x_2 \leq -1$$

$$-x_1 - 2x_2 \leq -2$$

$$x_1, x_2 \geq 0$$

The Min Cost Flow Problem

- Given N nodes connected with weighted arcs (links)
- Each node is either a source or a sink of flow
- Amount of flow originating at a node
  - $b_i>0$, source
- Amount of flow terminating at a node
  - $b_i<0$, sink
- All the flow generated must be consumed
  - $\Sigma_{i=1}^{N} b_i=0$
- c_{ij}=cost of a unit of flow traversing link (i,j)
- x_{ij}=amount of flow between node i and node j
- Objective:
  - route all the flow generated to the destinations with minimum cost

The Min Cost Flow Problem (2)

- The first constraint represents the flow conservation constraint

$$\min Z = \sum_{i,j} c_{ij} x_{ij}$$

$$s.t.$$

$$\sum_{j=1}^{N} x_{ij} - \sum_{k=1}^{N} x_{ki} = b_i \quad i = 1,2,\ldots,N$$

$$x_{ij} \geq 0 \quad i, j = 1,2,\ldots,N$$