APRICOT 2001

MPLS and its Applications

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What This Course is About

- What MPLS is
- What MPLS is good for
- MPLS protocol/mode comparisons & opinions
- Some applications of MPLS
- MPLS futures

What This Course is NOT About

- General networking
- Product comparisons
- Marketing

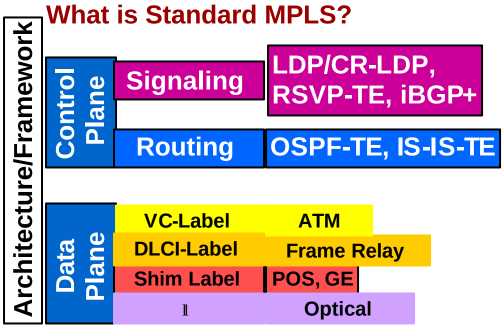
Tutorial outline

- **Basic concepts**
- Applications Overview
- Data Plane
- Control Plane
- MPLS and QoS
- Multi-Service over MPLS
- MPLS and VPNs
- MPLS and ASON
- Summary

What is MPLS?

- **MPLS = "Multi-Protocol Label Switching"**

What is Standard MPLS?



“Label Substitution” what is it?

One of the many ways of getting from A to B:

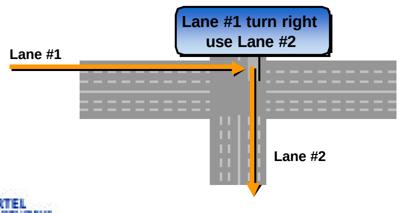
- ***BROADCAST***: Go everywhere, stop when you get to B, never ask for directions.
- ***HOP BY HOP ROUTING***: Continually ask who’s closer to B go there, repeat … stop when you get to B.

  “**Going to B?** You’d better go to X, its on the way”.
- ***SOURCE ROUTING***: Ask for a list (that you carry with you) of places to go that eventually lead you to B.

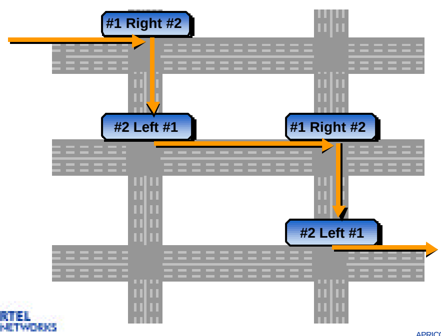
  “**Going to B?** Go straight 5 blocks, take the next left, 6 more blocks and take a right at the lights”.

“Label switching” what is it?

- **You want to travel from A to B. You ask some friends to go ahead of you. At every road they reserve a lane just for you. At every intersection they post a big sign that says for a given lane which way to turn and what new lane to take.**



Label Switched Path (LSP)



A label by any other name …

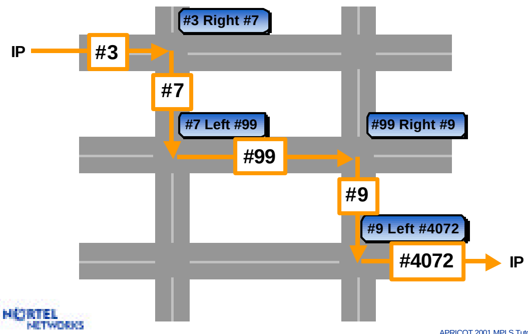
- There are many examples of label substitution protocols already in existence
  - ATM: label is called VPI/VCI and travels with cell
  - Frame Relay: label is called a DLCI and travels with frame
  - TDM: label is called a timeslot its implied, like a lane
  - X25: a label is an LCN
  - proprietary PORS, TAG etc.
  - frequency substitution: where label is a light frequency via DWDM, OXC etc.

What is a “LABEL”?

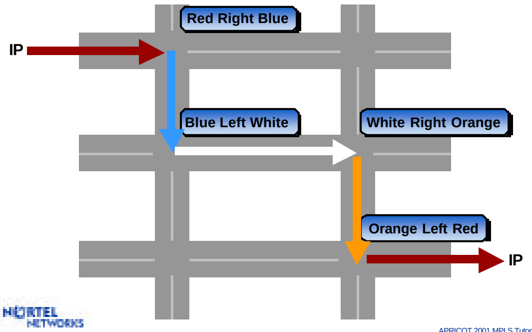
A property that uniquely identifies a flow on a logical or physical interface

- Labels are usually allocated on a per-interface basis, although in some cases they can also be allocated on a per-router basis

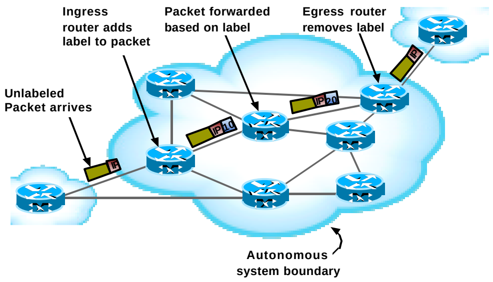
Label Switched Path



Optical Label Switched Path



A more current example…



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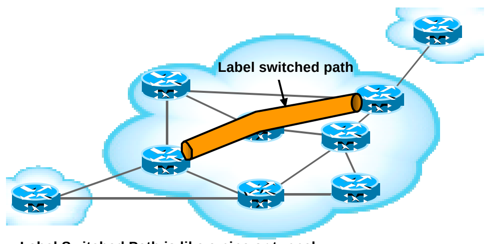


- Label Switched Path is like a pipe or tunnel
- While traveling on a label switched path, forwarding is based on the label only, not on destination IP address in packet

Terminology

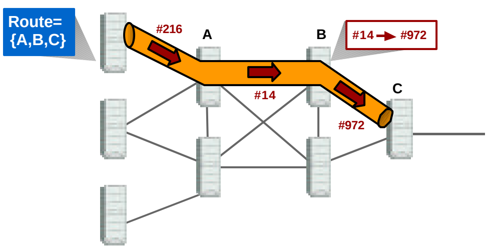
- **LSP = Label Switched Path**
- **LSR = Label Switching Router**
  - A router running MPLS software
- **Some use:**
  - LER = Router at start or end of LSP ("E" for "Edge")
  - LSR = Router in the middle of LSP

Label Switched Paths (LSPs)

LSPs ...

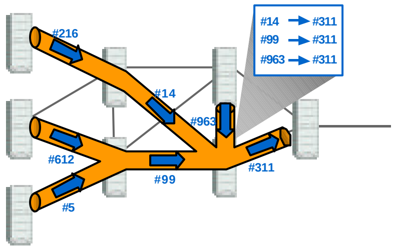
- **Are often called "tunnels"**
- **Are always unidirectional**
- **Can be either:**
  - **point-to-point, or**
  - **merging**

Point-to-point LSP



- **LSP follows route that source chooses. In other words, the control message to establish the LSP (label request) is *source routed*.**

Merging LSP



- LSP forms a "sink tree"
- The branches of the LSP always follows the same route as normal IP forwarding; that is, the *shortest path*

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Applications of MPLS

- A Unified IP/ATM solution
- Network-Based Virtual Private Networks
- Multi Service over MPLS
- IP Traffic Engineering
- Automatically Switched Optical Networks (ASON)
- Replacing iBGP in core routers

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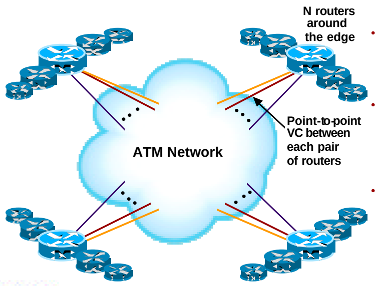
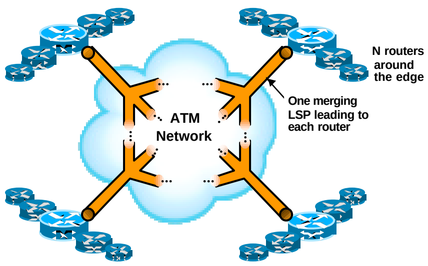
Unified IP/ATM solution
–Problem Definition



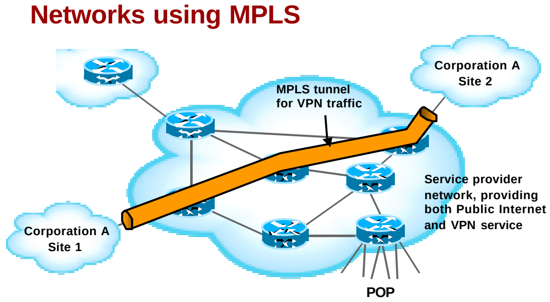
- Needs N^2 VCs in ATM network
  - requires N^2 cross-connections in core ATM switches
  - hard to manage
- Can generate up to N^3 routing update messages on link failure
  - can keep routers very busy processing all these messages
- Requires operations staff to work with both IP and ATM protocols
  - more training required
  - more places to look when something goes wrong

Unified IP/ATM with MPLS

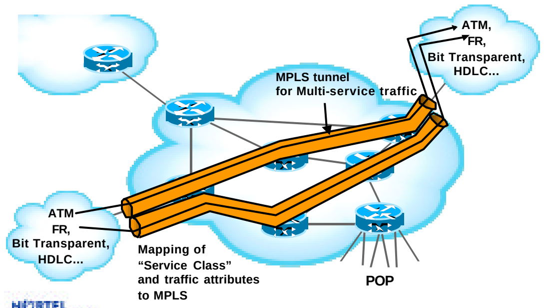


- Needs N merging LSPs
  - requires only NlogN cross-connections in core ATM switches
- N^3 routing update problems goes away
- Operations staff only needs to work with IP protocols

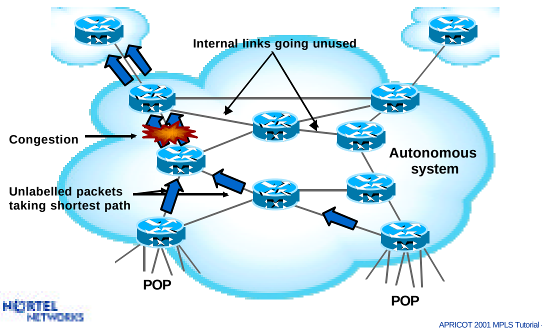
Network-Based Virtual Private Networks using MPLS



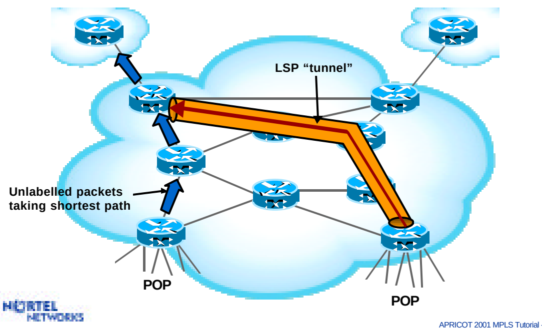
Multi-protocol Over MPLS

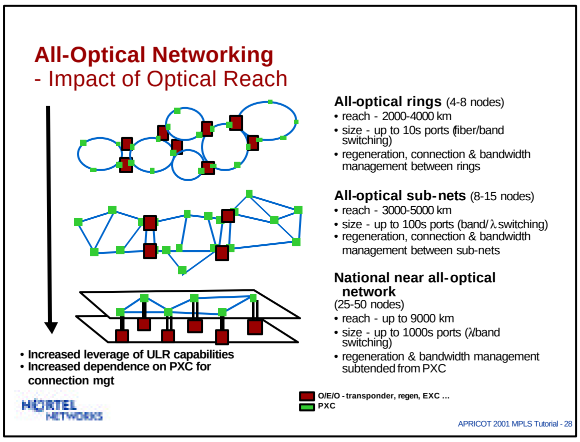


IP Traffic Engineering
–Problem Definition



Traffic Engineering using MPLS




All-Optical Networking
- Impact of Optical Reach
All-optical rings (4-8 nodes)
• reach - 2000-4000 km
• size - up to 10s ports (fiber/band switching)
• regeneration, connection & bandwidth management between rings
All-optical sub-nets (8-15 nodes)
• reach - 3000-5000 km
• size - up to 100s ports (band/λ switching)
• regeneration, connection & bandwidth management between sub-nets
National near all-optical network
(25-50 nodes)
• reach - up to 9000 km
• size - up to 1000s ports (λ/band switching)
• regeneration & bandwidth management subtended from PXC
• Increased leverage of ULR capabilities
• Increased dependence on PXC for connection mgt
O/E/O - transponder, regen, EXC ...
PXC
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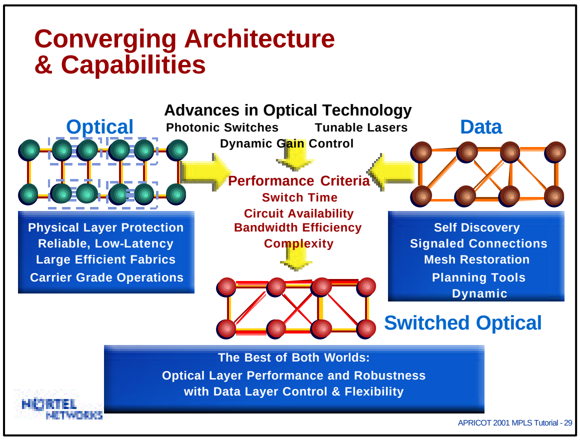
Converging Architecture & Capabilities
Advances in Optical Technology
Photonic Switches
Tunable Lasers
Dynamic Gain Control
Optical
Data
Performance Criteria
Switch Time
Circuit Availability
Bandwidth Efficiency
Complexity
Physical Layer Protection
Reliable, Low-Latency
Large Efficient Fabrics
Carrier Grade Operations
Self Discovery
Signaled Connections
Mesh Restoration
Planning Tools
Dynamic
Switched Optical
The Best of Both Worlds:
Optical Layer Performance and Robustness
with Data Layer Control & Flexibility
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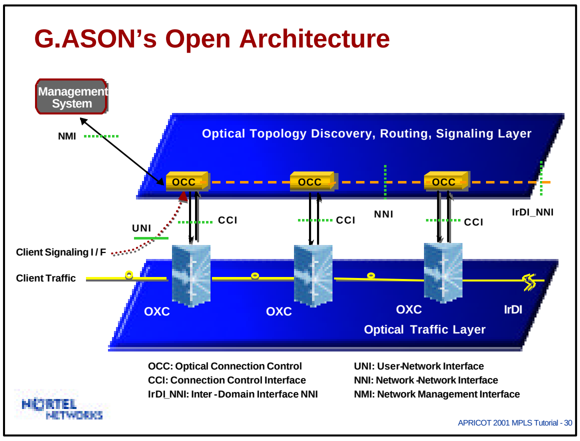
G.ASON's Open Architecture
Management System
NMI
Optical Topology Discovery, Routing, Signaling Layer
OCC
OCC
OCC
UNI
CCI
CCI
NNI
CCI
IrDI_NNI
Client Signaling I / F
Client Traffic
OXC
OXC
OXC
IrDI
Optical Traffic Layer
OCC: Optical Connection Control
CCI: Connection Control Interface
IrDI_NNI: Inter-Domain Interface NNI
UNI: User-Network Interface
NNI: Network-Network Interface
NMI: Network Management Interface
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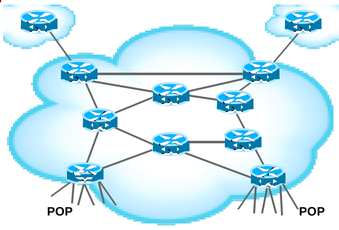
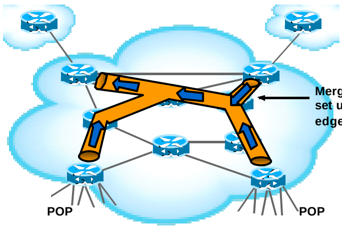
Replacing iBGP on interior routers
– The problem



- **All routers in the network run both iBGP and OSPF/IS-IS**
- **Running iBGP on lots of routers makes reaction to routing changes slower**

Replacing iiBGP on interior routers
– The solution



- **Interior routers run only OSPF/ISIS; edge routers still run both**
- **iBGP not needed because packets are traveling on an LSP**
  - Interior router forwards the packet based on the label
  - No knowledge of external destinations needed, hence no iiBGP

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- **Data Plane**
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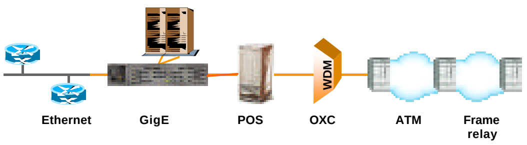
Data Plane

- **Label Encapsulations**
- Label Stacking

Upper layer consistency across lower layers



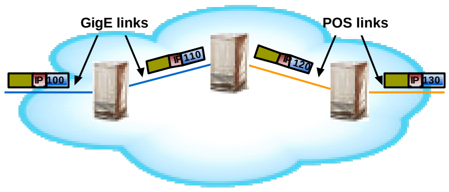
- **MPLS is "multiprotocol" below (link layer)**
- **Provides for consistent operations, engineering across multiple technologies**
- **Allows operators to leverage existing infrastructure**
- **Co-existence with other protocols is provided for**
  - eg. "Ships in the Night" operation with ATM, muxing over PPP

MPLS positioned as end-to-end forwarding paradigm

Important media types for MPLS today

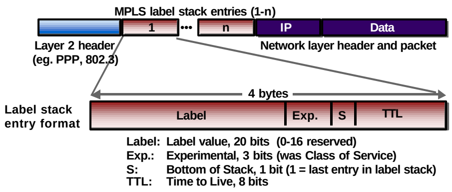
- **Packet over SONET (PoS) and Gigabit Ethernet (GigE)**
- **ATM with Shim Headers**
- **ATM with VPI/VCI Labels**
- **Frame Relay**
- **Optical**

PoS and GigE



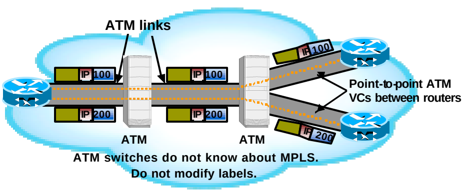
- "Packet over SONET" is really IP over PPP over SONET
- Gigabit Ethernet is really IP over Ethernet (running at gigabit speeds)
- Label is inserted before IP header

MPLS encapsulation
– PPP & Ethernet links



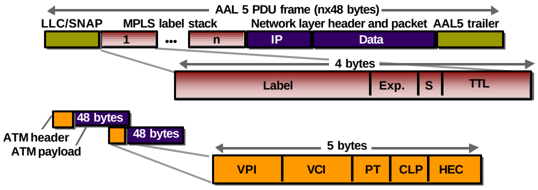
MPLS on PPP and Ethernet links uses a label stack (shim header) inserted between Layer 2 and Layer 3 headers

ATM with Shim Headers



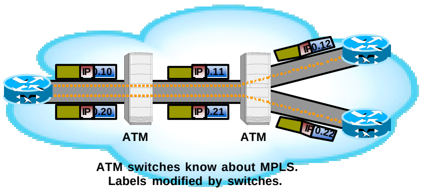
- Designed for existing router and ATM switch networks
- Routers connected by point-to-point ATM VCs
- IP packet has label prepended
- This method does not solve N^2 and N^3 problems mentioned earlier

MPLS encapsulation
– ATM with Shim Headers



- Labels carried in Label Stack; top label not modified by ATM switches
- VPI/VCI field identifies ATM VC
- LLC/SNAP identifies protocol that follows as "MPLS"
- This format heavily used, but not officially documented

ATM with VPI/VCI Labels

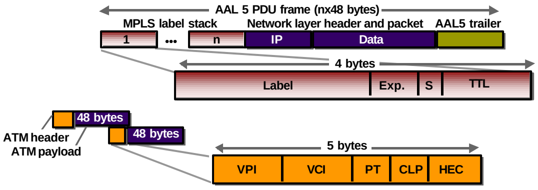


- This method intended to solve N² and N³ problems
- ATM switches enhanced to know about MPLS
- Labels carried in VPI/VCI field to allow switches to modify

ATM Switch Enhancements

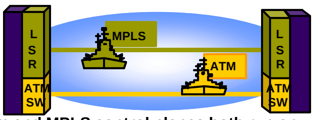
- **Data Plane -- No change required**
  - Data plane cannot tell difference between a VC and an LSP
- **Control Plane -- Add IP routing and MPLS signaling**
  - VCs are signaled using PNNI signaling
  - VCs are routed using PNNI routing
  - LSPs are signaled using MPLS signaling
  - LSPs are routed using IP routing

MPLS encapsulation
– ATM with VPI/VCI labels



- Top label value carried in VPI/VCI field of ATM header
- Top label stack entry contains a “0” in label field
- 2..n labels carried in label field of subsequent label stack entries

Ships in the Night

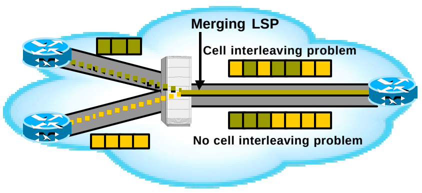


- ATM Forum and MPLS control planes both run on the same hardware but are isolated from each other, i.e. they do not interact
- This allows a single device to simultaneously operate as both an MPLS LSR and an ATM switch
- Important for migrating MPLS into an ATM network

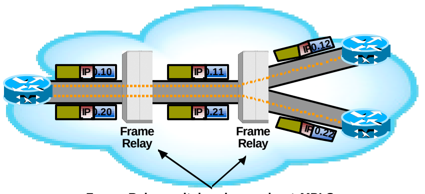
Ships in the Night requirements

- **Resource management**
  - VPI.VCI space partitioning
  - traffic management
    - bandwidth reservation
    - admission control
    - queuing and scheduling
    - shaping/policing
  - processing capacity
- **Bandwidth management**

VC-Merge Issue

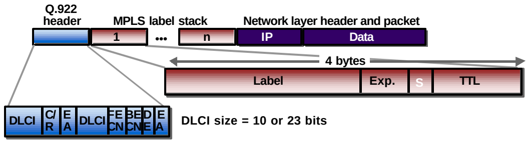


Frame Relay



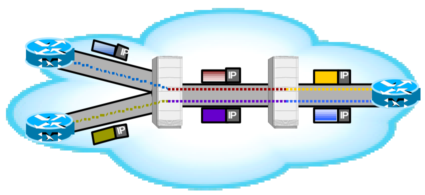
- This method defined, but not clear anyone is using it

MPLS encapsulation – Frame Relay



- Top label value carried in DLCI field of frame relay header
- Top label stack entry contains a “0” in label field
- 2..n labels carried in label field of subsequent label stack entries
- No cell interleave problem over Frame Relay

Optical

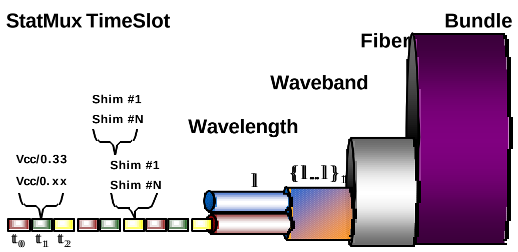


- Label not prepended to packet
- Instead is represented by a fiber number or a wavelength

Data Plane

- Label Encapsulations
- **Label Stacking**

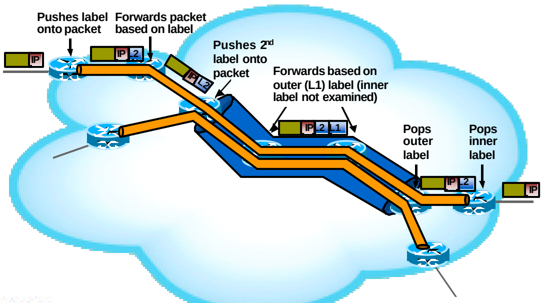
MPLS - Label Hierarchy



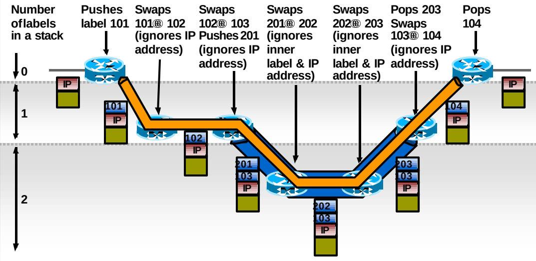
LSPs within LSPs

- Can put LSPs inside other LSPs
  - Very powerful – provides scalability
- Implemented by allowing packet to have more than one label at a time
  - Labels form a stack
- Router always forwards based on outermost or “top” label
- Can nest LSPs in this way to arbitrary depth
  - 2 or 3 is maximum we see today

Label Stacking Example



Label Stacking Details



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Control Plane

- **Signaling**
  - LDP
  - CR-LDP and RSVP-TE
- Constraint-based Routing

NORTEL NETWORKS

Terminology

- **Officially, LDP = "Label Distribution Protocol"**
- **Many people prefer:**
  "Label Distribution Protocol" -- Generic term
  "LDP" -- One specific example

NORTEL NETWORKS

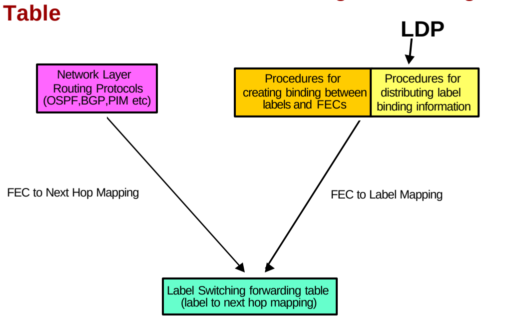
LDP: Uses

- **Creates merging LSPs**
- **LSPs follow same route as unlabelled packets**
- **No way to specify bandwidth or other traffic parameters**
- **Useful for:**
  - fast IP-aware forwarding over ATM
  - reducing routing table size on interior routers
  - creating VPN tunnels
- **Not useful for:**
  - traffic engineering

Terminology: FEC

- **FEC = "Forwarding Equivalence Class"**
- **Formally, a FEC is the set of packets that are forwarded in the same manner by a router**
- **For example, the set of packets that are traveling on an LSP**
- **However, because of the way LDP is used today, it can be thought of as the IP address of the router at which the LSP terminates**

Construction of Label Switching Forwarding Table



LDP: Modes of operation

- To run LDP, must make three mode choices:
  - Downstream-on-Demand <u>or</u> Downstream Unsolicited ?
    (the distribution mode)
  - Liberal <u>or</u> Conservative ?
    (the label retention mode)
  - Ordered <u>or</u> Independent ?
    (the control mode)
- Combinations of choices are possible

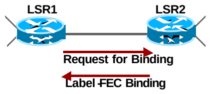
Label distribution - methods

Label distribution can take place using one of two possible methods:

Downstream Unsolicited Label Distribution

- LSR2 and LSR1 are said to have an "LDP adjacency" (LSR2 being the downstream LSR)
- LSR2 generates a label for the FEC and communicates the binding to LSR1
- LSR1 inserts the binding into its forwarding tables
- If LSR2 is the next hop for the FEC, LSR1 can use that label knowing that its meaning is understood

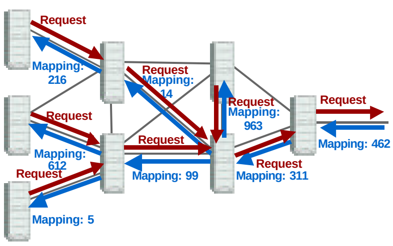
Downstream-on-Demand Label Distribution



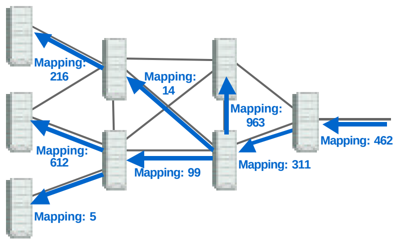
- LSR1 recognizes LSR2 as its next-hop for an FEC
- A request is made to LSR2 for a binding between the FEC and a label
- If LSR2 recognizes the FEC and has a next hop for it, it creates a binding and replies to LSR1
- Both LSRs then have a common understanding

Both methods are supported, even in the same network at the same time
For any single adjacency, LDP negotiation must agree on a common method

Downstream-on-demand label distribution

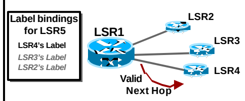


Downstream unsolicited label distribution



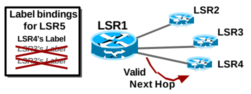
Label retention methods

Liberal Label Retention



- LSR maintains bindings received from LSRs other than the valid next hop
- If the next-hop changes, it may begin using these bindings immediately
- May allow more rapid adaptation to routing changes
- Requires an LSR to maintain many more labels

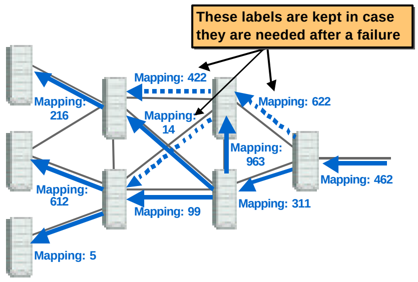
Conservative Label Retention



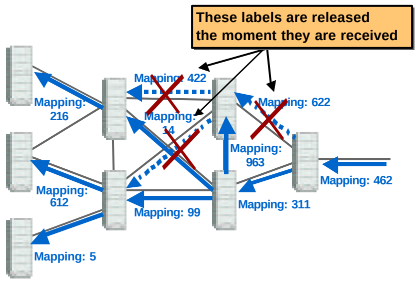
- LSR only maintains bindings received from valid next hop
- If the next-hop changes, binding must be requested from new next hop
- Restricts adaptation to changes in routing
- Fewer labels must be maintained by LSR

Label retention method trades off between label capacity and speed of adaptation to routing changes

Liberal retention mode



Conservative retention mode



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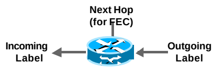
Distribution control:
Ordered vs Independent

MPLS path forms as associations are made between FEC next-hops and incoming and outgoing labels



	Ordered LSP Control	Independent LSP Control
Definition	• Label-FEC binding is communicated to peers if: - LSR is the 'egress' LSR to particular FEC - label binding has been received from upstream LSR • LSP formation 'flows' from egress to ingress	• Each LSR makes independent decision on when to generate labels and communicate them to upstream peers • Communicate label-FEC binding to peers once next-hop has been recognized • LSP is formed as incoming and outgoing labels are spliced together
Comparison	• Mechanism for consistent granularity and freedom from loops • Used for explicit routing and multicast • Requires more delay before packets can be forwarded along the LSP • Depends on availability of egress node	• Granularity may not be consistent across the nodes at the start • May require separate loop detection/mitigation method • Labels can be exchanged with less delay • Does not depend on availability of egress node

Both methods are supported in the standard and can be fully interoperable

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Two important combinations of modes

- **Downstream-on-demand, conservative, ordered**
  - uses fewer labels at a time
    - good for ATM or other hardware where the label range or cross-connect ability is limited
  - poorer performance during routing changes
    - more messages required
    - LSPs "break" temporarily → possible packet loss
- **Downstream unsolicited, liberal, ordered**
  - good performance during routing changes
    - no messaging required, thus very fast
    - LSP do not "break" → no packet loss
  - requires more labels, and more messaging when LSP is originally set up

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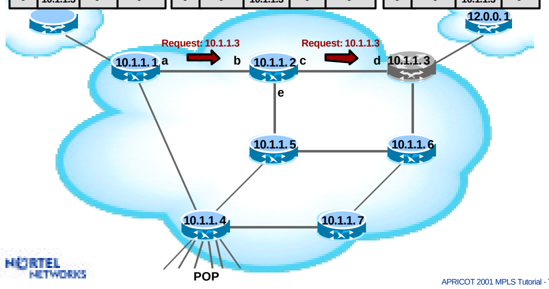
Downstream-on-demand, conservative, ordered

I/F in	Dest.	I/F out	Label out
-	10.1.1.3	-	-

I/F in	Label in	Dest.	I/F out	Label out
-	-	10.1.1.3	-	-

I/F in	Label in	Dest.	I/F out
-	-	10.1.1.3	-

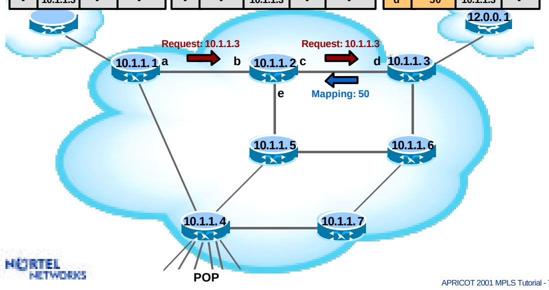


Downstream-on-demand, conservative, ordered

I/F in	Dest.	I/F out	Label out
-	10.1.1.3	-	-

I/F in	Label in	Dest.	I/F out	Label out
-	-	10.1.1.3	-	-

I/F in	Label in	Dest.	I/F out
d	50	10.1.1.3	-

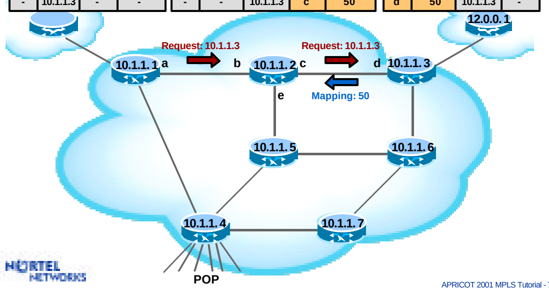


Downstream-on-demand, conservative, ordered

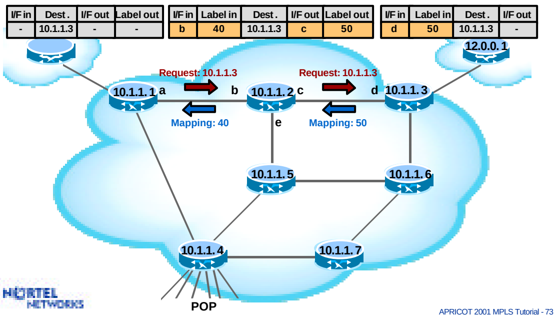
I/F in	Dest.	I/F out	Label out
-	10.1.1.3	-	-

I/F in	Label in	Dest.	I/F out	Label out
-	-	10.1.1.3	c	50

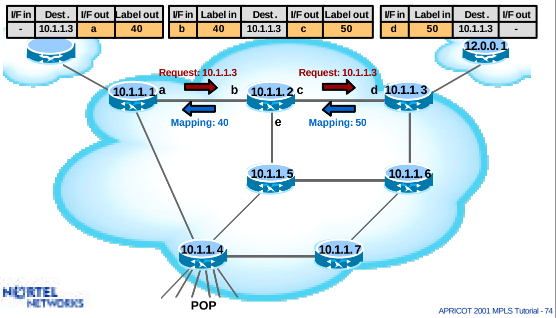
I/F in	Label in	Dest.	I/F out
d	50	10.1.1.3	-



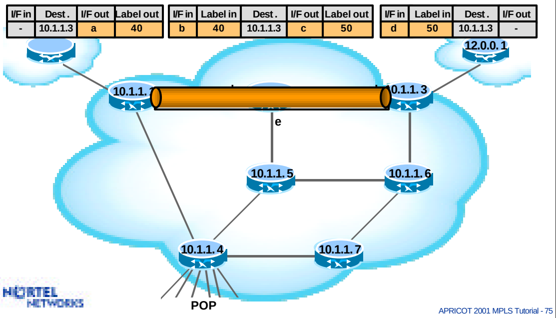
Downstream-on-demand, conservative, ordered



Downstream-on-demand, conservative, ordered



Downstream-on-demand, conservative, ordered

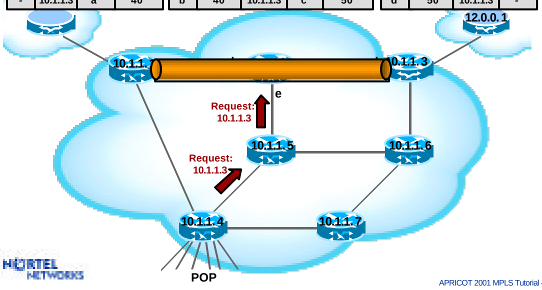


Downstream-on-demand, conservative, ordered

I/F in	Dest.	I/F out	Label out
-	10.1.1.3	a	40

I/F in	Label in	Dest.	I/F out	Label out
b	40	10.1.1.3	c	50

I/F in	Label in	Dest.	I/F out
d	50	10.1.1.3	-

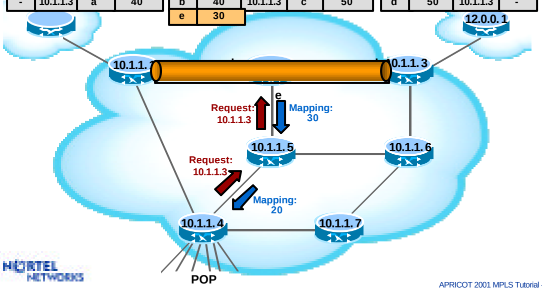


Downstream-on-demand, conservative, ordered

I/F in	Dest.	I/F out	Label out
-	10.1.1.3	a	40

I/F in	Label in	Dest.	I/F out	Label out
b	40	10.1.1.3	c	50
e	30			

I/F in	Label in	Dest.	I/F out
d	50	10.1.1.3	-

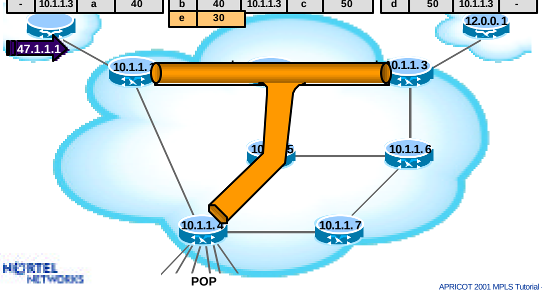


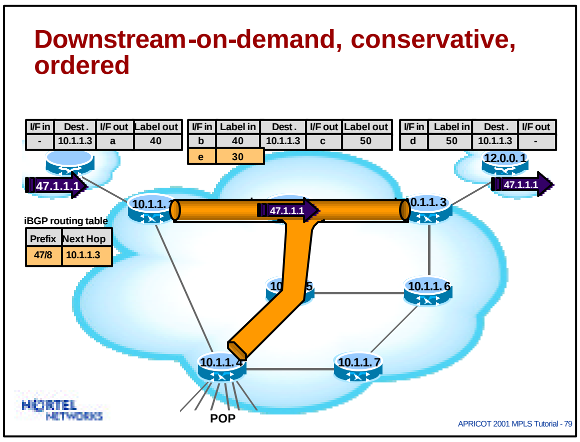
Downstream-on-demand, conservative, ordered

I/F in	Dest.	I/F out	Label out
-	10.1.1.3	a	40

I/F in	Label in	Dest.	I/F out	Label out
b	40	10.1.1.3	c	50
e	30			

I/F in	Label in	Dest.	I/F out
d	50	10.1.1.3	-




Downstream-on-demand, conservative, ordered
I/F in | Dest. | I/F out | Label out
- | 10.1.1.3 | a | 40
I/F in | Label in | Dest. | I/F out | Label out
b | 40 | 10.1.1.3 | c | 50
e | 30
I/F in | Label in | Dest. | I/F out
d | 50 | 10.1.1.3 | -
12.0.0.1
47.1.1.1
47.1.1.1
47.1.1.1
iBGP routing table
Prefix | Next Hop
47/8 | 10.1.1.3
10.1.1.3
10.1.1.6
10.1.1.4
10.1.1.7
POP
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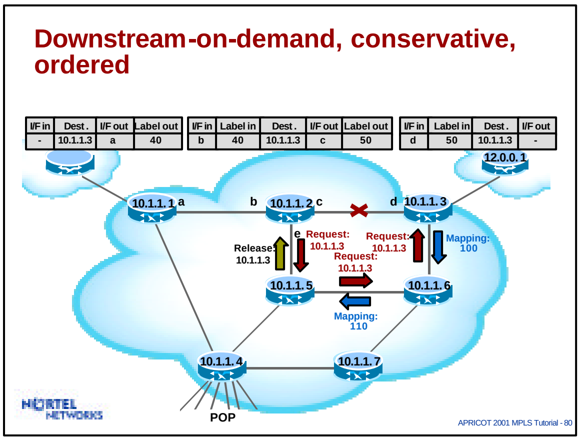
Downstream-on-demand, conservative, ordered
I/F in | Dest. | I/F out | Label out
- | 10.1.1.3 | a | 40
I/F in | Label in | Dest. | I/F out | Label out
b | 40 | 10.1.1.3 | c | 50
I/F in | Label in | Dest. | I/F out
d | 50 | 10.1.1.3 | -
12.0.0.1
10.1.1.1 a
b 10.1.1.2 c
d 10.1.1.3
e
Release: 10.1.1.3
Request: 10.1.1.3
Request: 10.1.1.3
Request: 10.1.1.3
Mapping: 100
Mapping: 110
10.1.1.5
10.1.1.6
10.1.1.4
10.1.1.7
POP
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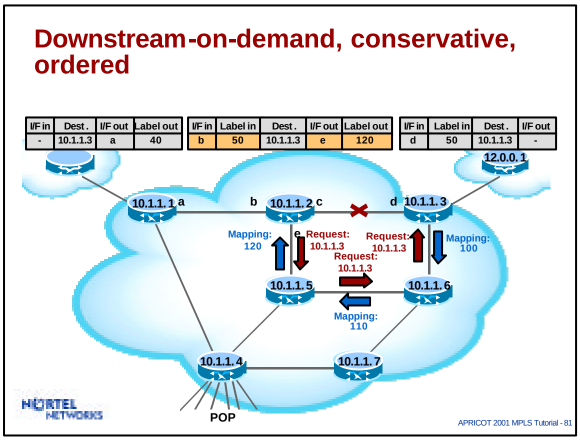
Downstream-on-demand, conservative, ordered
I/F in | Dest. | I/F out | Label out
- | 10.1.1.3 | a | 40
I/F in | Label in | Dest. | I/F out | Label out
b | 50 | 10.1.1.3 | e | 120
I/F in | Label in | Dest. | I/F out
d | 50 | 10.1.1.3 | -
12.0.0.1
10.1.1.1 a
b 10.1.1.2 c
d 10.1.1.3
e
Mapping: 120
Request: 10.1.1.3
Request: 10.1.1.3
Request: 10.1.1.3
Mapping: 100
Mapping: 110
10.1.1.5
10.1.1.6
10.1.1.4
10.1.1.7
POP
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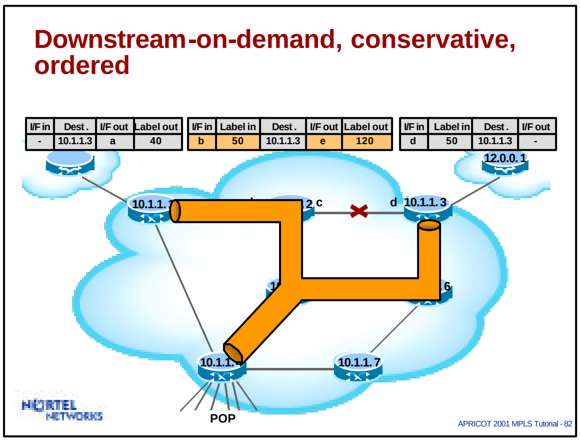
Downstream-on-demand, conservative, ordered
I/F in | Dest. | I/F out | Label out
- | 10.1.1.3 | a | 40
I/F in | Label in | Dest. | I/F out | Label out
b | 50 | 10.1.1.3 | e | 120
I/F in | Label in | Dest. | I/F out
d | 50 | 10.1.1.3 | -
12.0.0.1
10.1.1.3
c
d
POP
10.1.1.7
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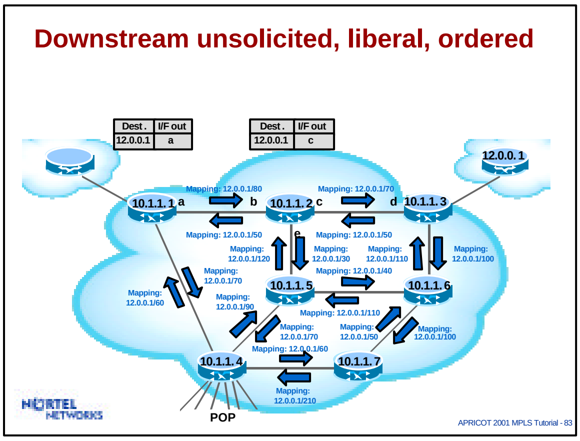
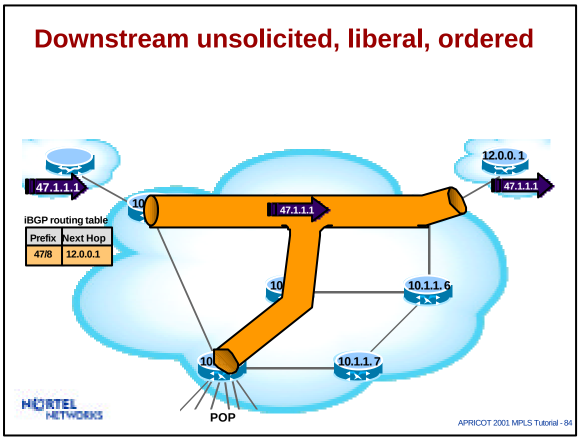

Downstream unsolicited, liberal, ordered
Dest. | I/F out
12.0.0.1 | a
Dest. | I/F out
12.0.0.1 | c
12.0.0.1
10.1.1.1
a
b
10.1.1.2
c
d
10.1.1.3
e
10.1.1.5
10.1.1.6
10.1.1.4
10.1.1.7
Mapping: 12.0.0.1/80
Mapping: 12.0.0.1/70
Mapping: 12.0.0.1/50
Mapping: 12.0.0.1/50
Mapping: 12.0.0.1/120
Mapping: 12.0.0.1/30
Mapping: 12.0.0.1/110
Mapping: 12.0.0.1/100
Mapping: 12.0.0.1/40
Mapping: 12.0.0.1/70
Mapping: 12.0.0.1/60
Mapping: 12.0.0.1/90
Mapping: 12.0.0.1/110
Mapping: 12.0.0.1/70
Mapping: 12.0.0.1/50
Mapping: 12.0.0.1/100
Mapping: 12.0.0.1/60
Mapping: 12.0.0.1/210
POP
APRICOT 2001 MPLS Tutorial - 83


Downstream unsolicited, liberal, ordered
47.1.1.1
iBGP routing table
Prefix | Next Hop
47/8 | 12.0.0.1
47.1.1.1
12.0.0.1
47.1.1.1
10.1.1.6
10.1.1.7
POP
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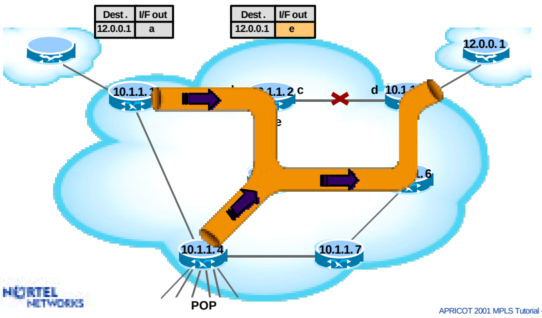
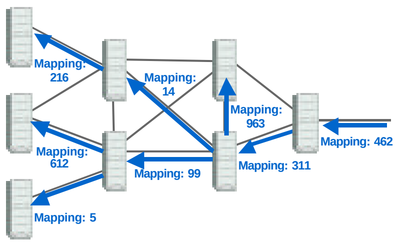
Downstream unsolicited, liberal, ordered



Independent mode



Control Plane

- Signaling
  - LDP
  - CR-LDP and RSVP-TE
    - common features
    - CR-LDP details
    - RSVP-TE details
    - comparison
- Constraint-Based Routing

CR-LDP and RSVP-TE

- CR-LDP = “Constraint-Routed LDP”
- RSVP-TE = “RSVP with Traffic Engineering Extensions”
- From a user’s prospective, these two protocols provide essentially the same function

CR-LDP and RSVP-TE: Uses

- Used to set up point-to-point LSPs
- LSPs can follow any path
- Can specify QoS parameters for LSP
- Useful for:
  - Traffic Engineering of Public Internet traffic
  - Traffic Engineering of VPN tunnels

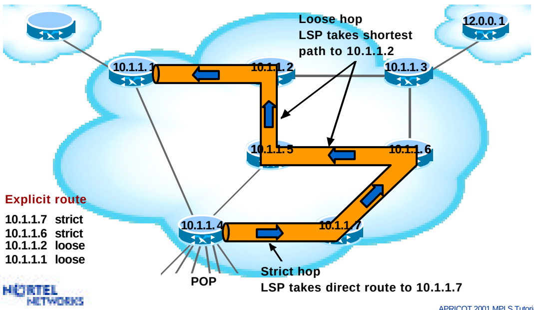
Common features

- Operate in (Downstream-on-Demand, Conservative, Ordered) mode
- Important Features:
  - Explicit route
  - QoS specification
  - LSP preemption
  - LSP modification
- Also, LDP sets up LSPs automatically, while CR-LDP and RSVP-TE typically require some sort of external intervention

Common features: Explicit route

- LSP route is specified as a sequence of router addresses
- Each hop between two routers in the path is either:
  - Strict if the two routers must be directly connected
  - Loose if other routers may appear in between
- On loose hops, the route taken between the nodes is the shortest path (as indicated by the routing table)
- The simplest explicit route is a single loose hop from the ingress router to the egress router

Common features: Explicit route example



Common features: QoS specification

- Can specify resources to allocate to LSP
  - example is the bandwidth to reserve on each link
- In general, QoS specified using token buckets
- The simplest QoS specification is to simply request Best Effort service, in which case no resources are allocated

Common features:
LSP preemption

- 8 priority levels (0 = highest, 7 = lowest)
- Each LSP has a setup priority and a holding priority
- At LSP setup, if there are insufficient free resources to setup the new LSP, then any old LSP whose holding priority is lower than the setup priority of the new LSP can be bumped

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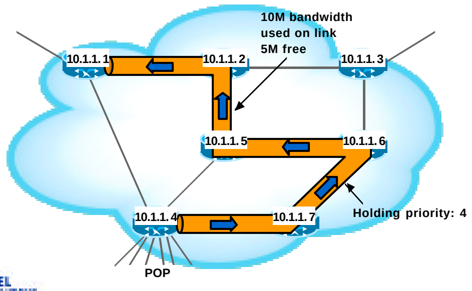
Common features:
LSP preemption example



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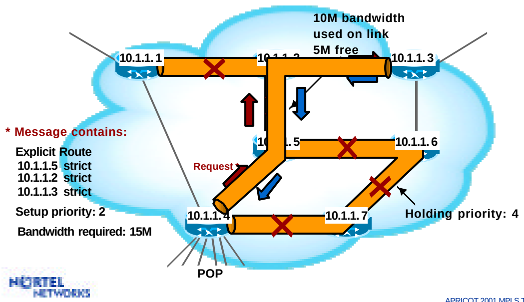
Common features:
LSP preemption example



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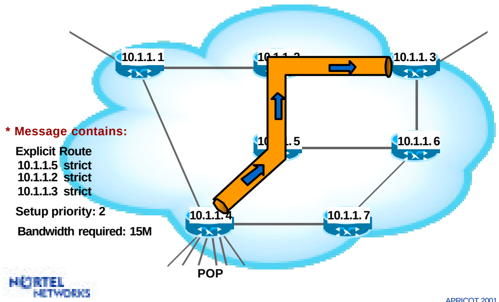
Common features: LSP preemption example



Common features: LSP modification

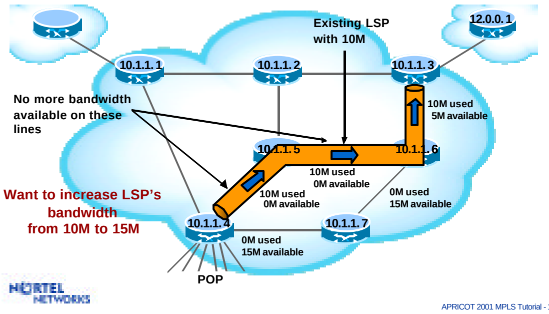
- Want to be able to modify attributes of an existing LSP
- Some modifications are easy
  - e.g., decrease in bandwidth, or change in holding priority
- Some modifications are harder
  - increase in bandwidth
- Problem comes when the path of the LSP must be changed
- Don't want to disrupt traffic flowing on the LSP while doing this

Common features: LSP modification

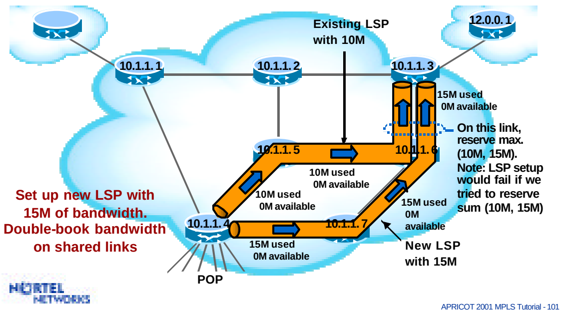
Steps to modify an LSP ("make-before-break" method):

1) Set up a new LSP that has the desired characteristics
2) Where old and new LSP take the same route, reserve Max(old,new) and not Sum(old,new)
   - for example, bandwidth on a given link
3) Once new LSP is set up, move traffic from old to new
4) Finally, tear down old LSP, releasing resources used only by it

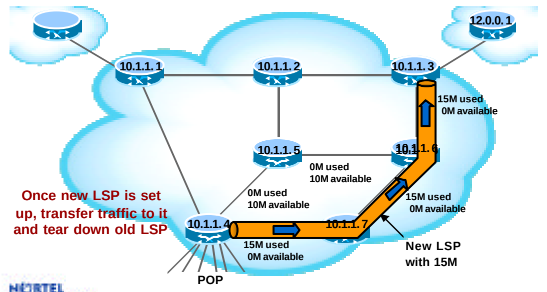
Common features:
LSP modification example



Common features:
LSP modification example



Common features:
LSP Modification example



CR-LDP details

- CR-LDP is an extension to LDP
- Like LDP, runs over TCP
- Uses existing LDP messages, but defines additional TLVs for the messages

CR-LDP details: Additions to LDP

- **Explicit Route TLV**
- **Traffic Parameters TLV**

- Other additions include:
  - Preemption TLV (with Setup and Holding priorities)
  - LSPID TLV
    (used for "make-before-break" modification)
  - Route Pinning TLV
    (allow or prevent route optimization)
  - Resource Class TLV
    (take or avoid links with certain attributes)

CR-LDP details: Traffic parameters

U	F	Traf. Param. TLV	Length
Flags	Frequency	Reserved	Weight
Peak Data Rate (PDR)			
Peak Burst Size (PBS)			
Committed Data Rate (CDR)			
Committed Burst Size (CBS)			
Excess Burst Size (EBS)			

- 32 bit fields are short IEEE floating point numbers
- Any parameter may be used or not used by selecting appropriate values

Flags: control "negotiability" of parameters

Frequency: constrains the variable delay that may be introduced

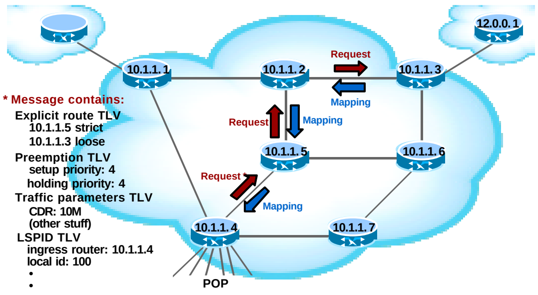
Weight: of the CRLSP in the "relative share"

Peak rate: (PDR+PBS) maximum rate at which traffic should be sent to the CRLSP

Committed rate: (CDR+CBS) the rate that the MPLS domain commits to be available to the CRLSP

Excess Burst Size: (EBS) to measure the extent by which the traffic sent on a CRLSP exceeds the committed rate

CR-LDP details: Example



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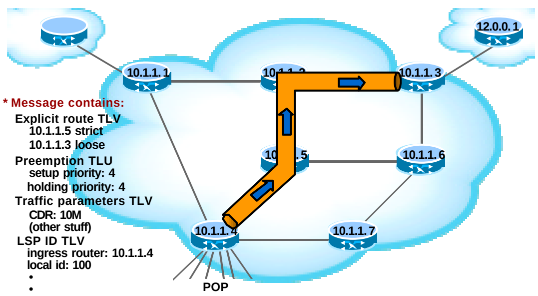
CR-LDP details: Example



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RSVP-TE details

- RSVP-TE is an extension of “classical” RSVP
- Runs directly over IP
- Uses Path messages (= Label Request) and Resv messages (= Label Mapping)
- Extends classical RSVP with new objects (= TLVs) for these messages

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RSVP-TE details: Classical RSVP

- Designed in early 90's
- Makes QoS reservations between hosts
  - for example, between a server and a workstation
- Has no concept of labels and LSPs
  - packets assumed to travel unlabelled
- No explicit route concept; reservations made along shortest path

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RSVP-TE details: Differences from classical RSVP

- Concept of labels and LSPs
- Explicit routes
- LSP attributes (including Setup and Holding priorities)
- "make-before-break" modification
- Record route
  (record the route of an LSP set up with loose hops)

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RSVP-TE details: QoS specification

- Based on integrated services (int-serv) model
- Three service classes:
  - Class-of-service: LSP provides best-effort service
  - Guaranteed Load: LSP provides hard delay bounds
  - Controlled Load: LSP provides good service, but no hard delay bounds

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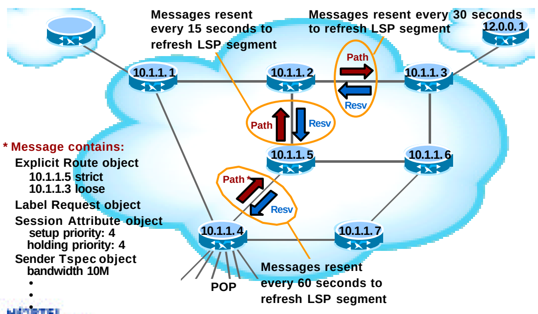
RSVP-TE details: Soft state

- **RSVP-TE (like classical RSVP) is a soft-state protocol**
- **Path and Resv messages must be resent to refresh the LSP and keep it alive**
- **This serves two purposes:**
  - RSVP-TE runs directly over IP, so resending makes sure the information gets through even if some messages are lost
  - no need to explicitly tear down an LSP -- just stop refreshing it instead
- **Messages resent on a per-hop basis, not end-to-end**

RSVP-TE details: Example



RSVP-TE details: Refresh reduction

- **Each Path and Resv message must be refreshed**
- **In a network with many LSPs, this requires lots of messages**
- **Hence the Refresh Reduction Extension**
- **This allows a router to send a single compact message that refreshes lots of LSPs at once**

CR-LDP and RSVP-TE comparison

	CR-LDP	RSVP-TE
Based on	LDP	Classical RSVP
Messages	Request ® ¬ Mapping	Path ® ¬ Resv
Transport	Runs over TCP	Runs over IP
State model	Hard state – explicit setup – no refresh – explicit teardown	Soft state – explicit setup – refresh required – implicit teardown

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CR-LDP and RSVP-TE comparison

	CR-LDP	RSVP-TE
Explicit Route	Strict and loose routes	Strict and loose routes
QoS Specification	ATM-TM model	Int-serv model
LSP Preemption	8 setup and holding priorities	8 setup and holding priorities
LSP Modification	Make-before-break method	Make-before-break method

NORTEL NETWORKS

CR-LDP and RSVP-TE comparison

	CR-LDP	RSVP-TE
Early Adopters	Nortel, Sycamore	Cisco, Juniper
Supporters	Host of others	Host of others
Notable Points	New Protocol Simpler Protocol	Poorly Specified
Notable Challenges	Interoperability	Interoperability Scalability

Nortel is Developing Both

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Control Plane

- Signaling
  - LDP
  - CR-LDP and RSVP-TE
- **Constraint-Based Routing**
  - Route Selection
  - Information Flooding through IGP
  - Feedback ala PORS to scale CR

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Route selection: The problem

- **CR-LDP and RSVP-TE support both explicit route and QoS reservation**
- **But if QoS resource are not available somewhere on the specified route, LSP setup will fail**
- **How to find a route with sufficient available resources?**

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Route selection: Option 1

- **One option is operator trial-and-error:**
  - operator selects a route he/she thinks is likely
  - tells ingress router to try route
  - if LSP fails, operator tries another route
- **This approach reasonable in a network with only a few LSPs, but not in a network with lots of LSPs**

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Route selection: Option 2

- **Another option is offline computation**
- **This method computes routes for ALL the LSPs in the network in one go:**
  - operator provides some constraints on routes
  - an offline planning tool selects the best route for all LSPs in the network, given the constraints
  - resulting routes are downloaded to ingress routers
  - ingress routers set up LSPs (using strict explicit routes)
- **This option will provide the best solution, but adding "one more LSP" to fix some problem is painful**

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Route selection: Option 3

- **A third option is online computation**
  - operator provides some constraints on the LSP's route
  - ingress router uses network information to compute a route (a strict explicit route)
  - ingress router sets up LSP using computed route
- **This approach makes it easy to add LSPs incrementally, and rerouting LSPs in failure situations**

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Route selection: Optimal

- **Options can be combined if there are multiple LSPs per FEC**
- **Combining Option 2 and Option 3 provides an attractive solution**
  - Offline Planning provides Engineered routes
  - Constraint based routing adjusts only those LSPs that cannot be satisfied due to network changes

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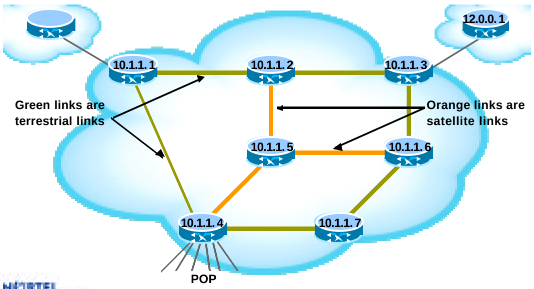
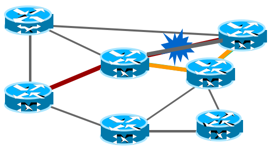
Route selection: Constraints

- **In options 2 and 3, operator can specify constraints on the route:**
  - route must pass through or avoid certain nodes
  - route must satisfy a given QoS constraint
  - route must avoid certain links and/or must include other links
- **The last form of constraint is a constraint on the link resource class (also known as the "link color")**

Route selection: Link color example

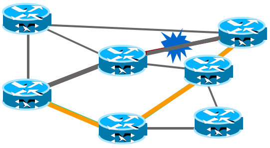


TE Recovery Solutions Local Repair



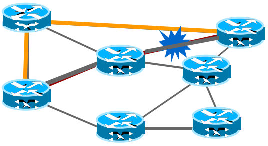
- **Locally switch to an alternate**
- **Bandwidth issues**
- **Fastest but least optimal**

TE Recovery Solutions
Global Backup



- Switch over to an alternate pre-established path
- Bandwidth issues
- Faster but less optimal

TE Recovery Solutions
Global Repair

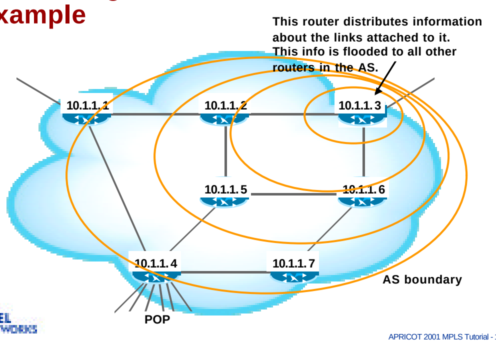


- Global Recalculate a path after the failure
- Bandwidth no issues
- Slowest but most efficient

Distributing network information

- **To do online route computation, ingress router needs:**
  - topology of the network
  - available bandwidth on each link
  - color of each link
- **This info is distributed using OSPF or IS-IS**
- **Why OSPF or IS-IS?**
  - these are link state protocols
  - work by distributing link state info to every router in network
  - as originally defined, distributed address and link up/down info
  - easy to extend to link color and bandwidth info (known as the "TE extensions")
  - RIP is not a link state algorithm -- thus not suitable

Distributing network information: Example



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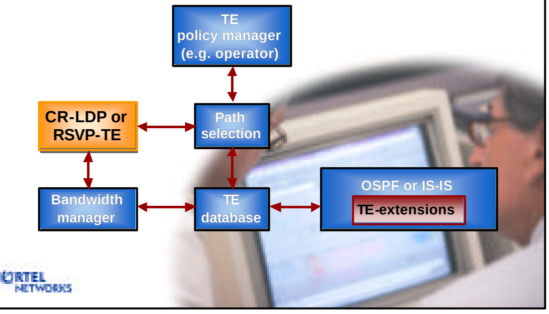
Components for online computation



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Online computation steps

1) Routers distribute QoS and color info using OSPF or IS-IS
2) Operator provides constrains on route
3) Ingress router computes acceptable route
   - CSPF (= Constrained Shortest Path First) algorithm
   - shortest path that satisfies the constraints
4) Ingress router uses CR-LDP or RSVP-TE to signal LSP

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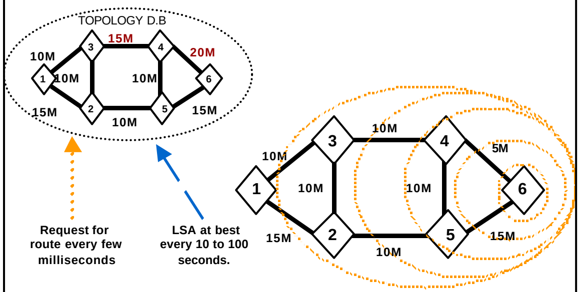
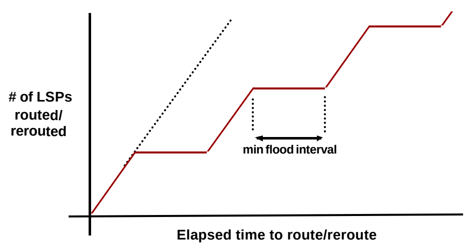
A small problem …

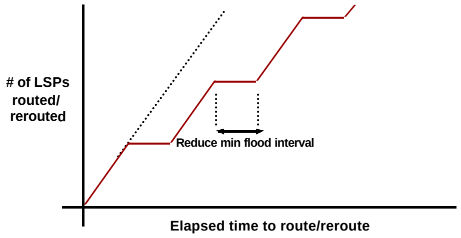
- **OSPF/ISIS can only flood updated bandwidth and color info every so often**
  – Uses too much bandwidth and CPU otherwise
- **If LSPs are being set up rapidly, then information at ingress router can be out-of-date**
  – Bandwidth that looks available could have already been taken
  – LSP setup may fail
- **Two possible solutions:**
  1) Have transit router that fails LSP flood updated bandwidth info
  2) Pass back updated bandwidth info in failure message (= "Feedback" method)



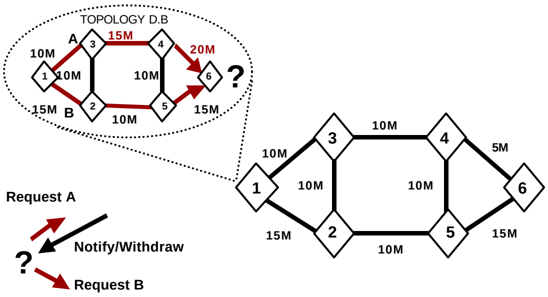
- **Distribution of link resource information via OSPF/IS-IS for TE will not be timely enough when many LSPs must be established or rerouted quickly because LSP arrival rate exceeds minimum flood interval by 4-5 orders of magnitude**



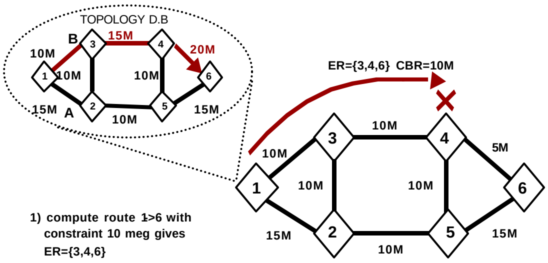
- **Result is that LSPs establish in bursts with minimum flood interval sized pauses. In other words we may block an LSP from establishing for up to the minimum flood interval even though there is a route.**



- Reducing the minimum flooding interval does not help much because it cannot be reduced to anywhere close to what is required to make a significant difference



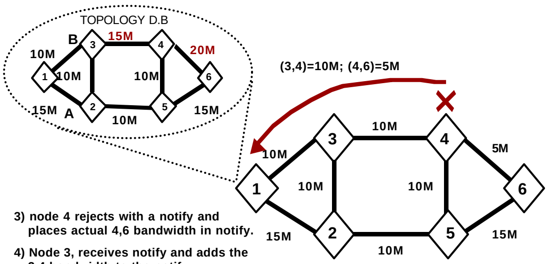
- Another alternative is to make the route computation non deterministic (guess) but this results in non lowest cost routes in the best case or excessive fruitless hunting in the worst case.



1) compute route 1>6 with constraint 10 meg gives ER={3,4,6}

2) format label request and launch it along 3,4,6 ER.

Better solution. Learn from your mistakes.



3) node 4 rejects with a notify and places actual 4,6 bandwidth in notify.

4) Node 3, receives notify and adds the 3,4 bandwidth to the notify.

5) Node 1, receives the notify with the real avail bandwidth along the path:

(1,3)=10; (3,4)=10; (4,6)=5

Feedback a correction for the mistake

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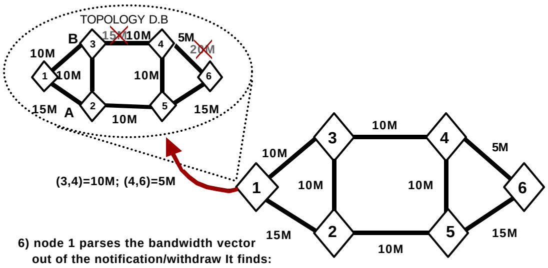

6) node 1 parses the bandwidth vector out of the notification/withdraw It finds:
(3,4)=10; (4,6)=5

7) node 1 overwrites the (3,4) old bandwidth value of 15 with the more recent value 10 and then the (4,5) link value with the value 5.

Incorporate the correction into your topology

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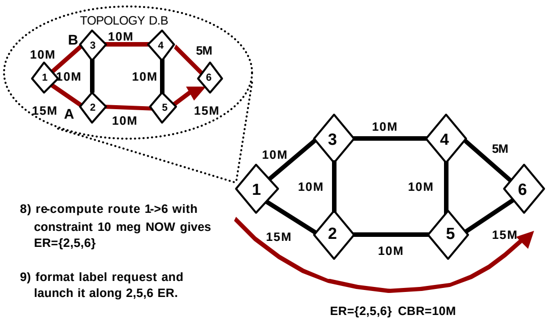

8) re-compute route 1->6 with constraint 10 meg NOW gives ER={2,5,6}

9) format label request and launch it along 2,5,6 ER.

And start again from a more up to date view.

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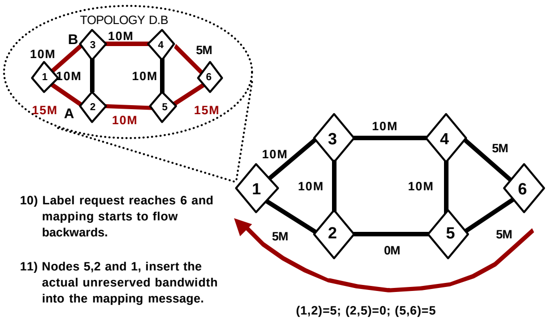

10) Label request reaches 6 and mapping starts to flow backwards.

11) Nodes 5,2 and 1, insert the actual unreserved bandwidth into the mapping message.

This time we will succeed but our success will cause the topology to drift yet again.

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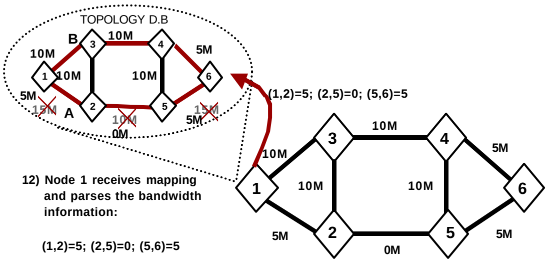

12) Node 1 receives mapping and parses the bandwidth information:

(1,2)=5; (2,5)=0; (5,6)=5

13) Node 1 overwrite the (1,2) bandwidth with 5, the (2,5) with 0 and the (5,6) with 5.

We have now stopped the drift and subsequent requests have a more accurate view

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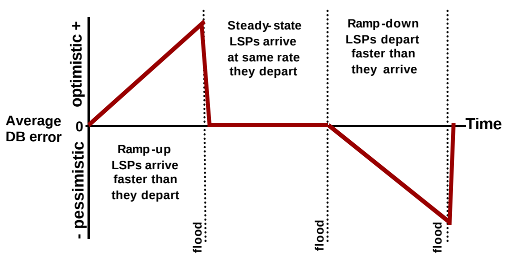

- **We define the error in topology database as being *optimistic* when DB shows more available bandwidth than real network and *pessimistic* when DB shows less. Without feedback we stay optimistic till next flood arrives.**

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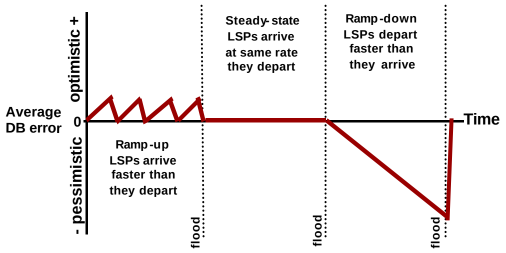


- With feedback, the optimism is more tightly bounded and snaps back to reality as we learn about our optimism through mistakes. We thus makes less mistakes. Feedback does not help with pessimism.

U	F	0x8..To Be Determined	Length
Bandwidth Unreserved at Holding Priority 0 in bytes per second (float)			
Bandwidth Unreserved at Holding Priority 1 in bytes per second (float)			
2			
3			
4			
5			
6			
Bandwidth Unreserved at Holding Priority 7 in bytes per second (float)			
IP4v4 address of near end			
IP4v4 address of near end			

- CR-LDP can carry an optional TLV in the notification, mapping and withdraw messages to carry this information and procedures to populate on propagation/launching of these messages
(also a similar TLV for IPv6)

Tutorial outline

- Basic concepts
- Applications Overview
- Data Plane
- Control Plane
- **MPLS and QoS**
- Multi-Service over MPLS
- MPLS and VPNs
- MPLS and ASON
- Summary

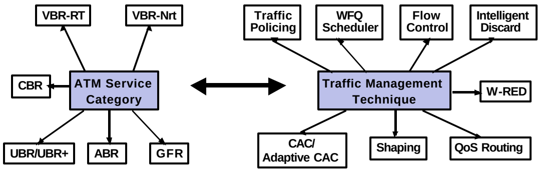
MPLS & QoS

- Emerging QoS Requirements
- ATM QoS
- IP QoS
- MPLS QoS
- Example Applications

Emerging QoS Requirements

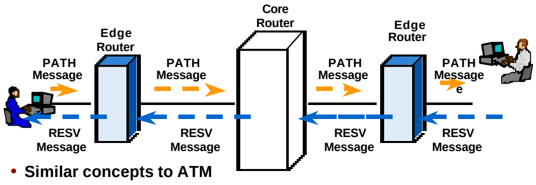
- Enable the offering of multiple services with various soft and hard guarantees:
  - ATM Service Categories
  - Leased Line / Circuit Emulation
  - Premium VPNs
  - Class-based VPNs
  - DiffServ
  - Voice over IP
- Enabling making trade-offs between cost, scalability, complexity, and guarantees/SLAs

ATM Traffic Management



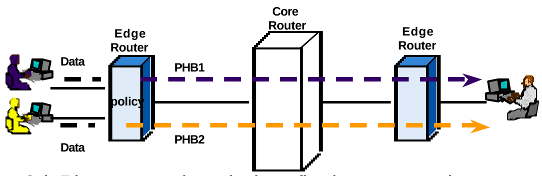
- Support a Rich Set of QoS Capabilities
- Provide Hard Guarantees on loss, delay, and delay variance
- Trade off on network complexity and network scalability
- Limited aggregation using VPs and Differentiated UBR and UBR+

IP QoS Mechanisms-1:
Int-Serv Architecture



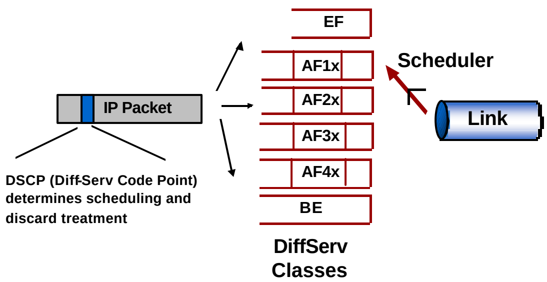
- Similar concepts to ATM
- Provides hard per-flow QoS guarantees, at the expense of complexity and reduced scalability
- Does not address QoS routing or Traffic Engineering

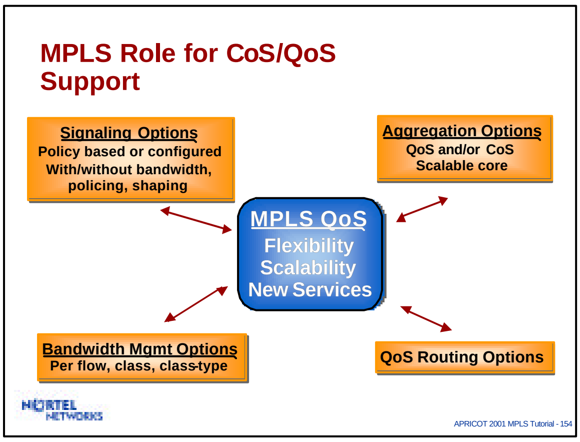
IP QoS Mechanisms-2:
Diff-Serv Architecture



- Only Edge routers need to maintain per flow (or per aggregate) state and possibly perform policing and shaping
- Core routers need only to forward packets according to the specified PHB (Per Hop Behavior) in the DS byte
  - no per flow state, hence scaleable to a large number of flows
- Provide aggregate SLAs for each traffic class (e.g. gold, silver, bronze)

DiffServ Forwarding




MPLS Role for CoS/QoS Support
Signaling Options
Policy based or configured
With/without bandwidth, policing, shaping
Aggregation Options
QoS and/or CoS
Scalable core
MPLS QoS
Flexibility
Scalability
New Services
Bandwidth Mgmt Options
Per flow, class, class-type
QoS Routing Options
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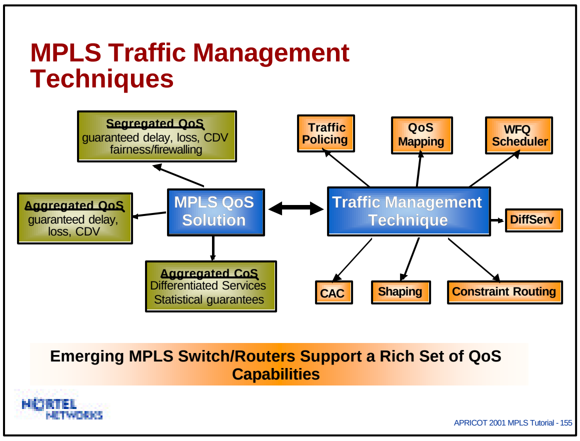
MPLS Traffic Management Techniques
Segregated QoS
guaranteed delay, loss, CDV
fairness/firewalling
Traffic Policing
QoS Mapping
WFQ Scheduler
Aggregated QoS
guaranteed delay, loss, CDV
MPLS QoS Solution
Traffic Management Technique
DiffServ
Aggregated CoS
Differentiated Services
Statistical guarantees
CAC
Shaping
Constraint Routing
Emerging MPLS Switch/Routers Support a Rich Set of QoS Capabilities
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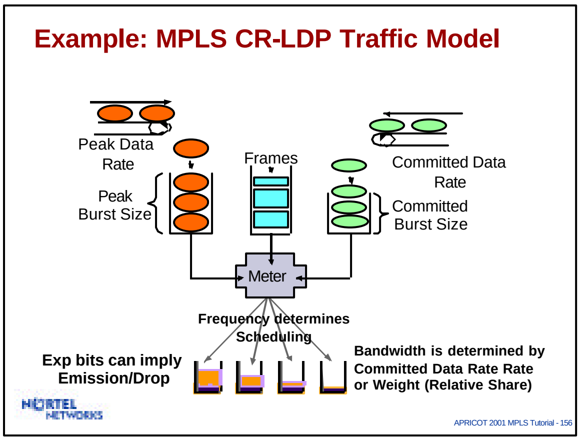
Example: MPLS CR-LDP Traffic Model
Peak Data Rate
Peak Burst Size
Frames
Committed Data Rate
Committed Burst Size
Meter
Frequency determines Scheduling
Exp bits can imply Emission/Drop
Bandwidth is determined by Committed Data Rate Rate or Weight (Relative Share)
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MPLS Bandwidth Management:
User Options

Shared Pool

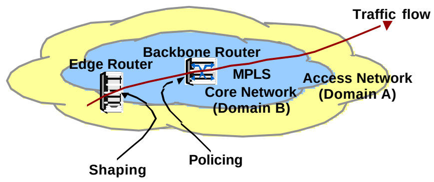
Partitioned

- Simplest
- Least BW fragmentation
- Least OSPF advertising overhead
- No Min guarantee for any class

- More configuration
- Link fragmentation
- More OSPF overhead
- Min-guarantee for each class

Hybrid sharing is allowed
Both options allow for overbooking

MPLS Traffic Shaping & Policing



Used when the Access and Core Networks belong to Non-trusting Administrative Domains

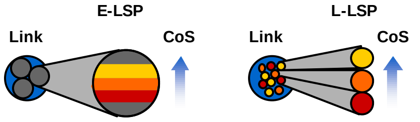
MPLS & DiffServ:
A Complementary Combination

- **Both MPLS & DiffServ have same scalability goals:**
  - Aggregation of traffic on Edge
  - Processing of Aggregate only in Core
- **DiffServ can augment MPLS Signaling and Forwarding:**
  - **Signaling**: enhance LDP, CR-LDP, RSVP-TE with explicit Class-of-Service indication (e.g. EF, AF, BE)
  - **Forwarding**: DiffServ Code Points can be mapped to the MPLS label EXP Bits, to indicate individual packets discard and emission priorities
- **Two types of LSPs are defined: L-LSPs & E-LSPs**

MPLS and Diff-Serv

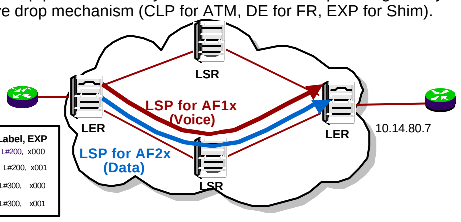
- E-LSPs give fewer “fatter” LSPs
- L-LSPs give more “thinner” LSPs

MPLS LSP cross-sections



Label inferred LSP (L-LSP)

L-LSPs: The scheduling treatment is inferred from the label, and the drop precedence may be inferred in the encapsulating link layer selective drop mechanism (CLP for ATM, DE for FR, EXP for Shim).



<FEC,CoS>	Label, EXP
10.14.80.7, AF11	L#200, x000
10.14.80.7, AF12	L#200, x001
10.14.80.7, AF21	L#300, x000
10.14.80.7, AF22	L#300, x001

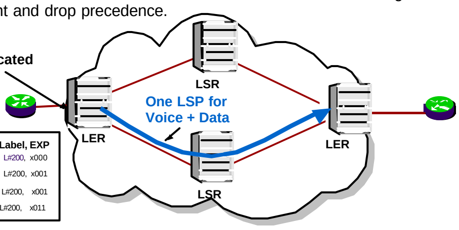
LDP/CR-LDP or RSVP establishes LSPs for each <FEC, CoS>

Requires signaling of Diff-Serv TLV

EXP inferred LSPs (E-LSP)

The EXP field of the MPLS Shim header indicates the scheduling treatment and drop precedence.

CoS is indicated in EXP bits

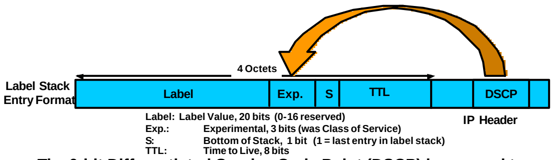


<FEC,CoS>	Label, EXP
10.14.80.7, AF11	L#200, x000
10.14.80.7, AF12	L#200, x001
10.14.80.7, AF21	L#200, x001
10.14.80.7, AF22	L#200, x011

Uses LDP/CR-LDP or RSVP to establish the LSPs for each FEC

Mapping of CoS to MPLS EXP bits is signaled or configured

DiffServ and E-LSP Mapping



- The 6-bit Differentiated Service Code Point (DSCP) is mapped to the 3-bit MPLS EXP Bits
- Mapping flexibility is provided through signaling or provisioning
- Allows a single LSP to support up to 8 Diff-Serv Behavior Aggregates (CoS)
- E-LSPs Cannot be supported over ATM links

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Applicability

- On ATM and FR, only L-LSPs are supported
  - because hardware supports this directly
- Over Ethernet and PPP (e.g. Packet-over-SONET), can have both E-LSPs and L-LSPs

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E-LSPs and L-LSPs comparison

	E -LSP	L-LSP
Number of LSPs	Small	Higher
Bandwidth Mgmt	Aggregate	Per QoS
Net Scalability	High	Lower
QoS Guarantee	Soft	Hard

- Trade-off between QoS control and network scalability
- Both can be used in same network for different applications

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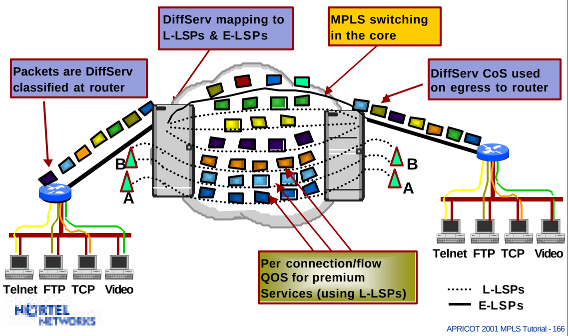
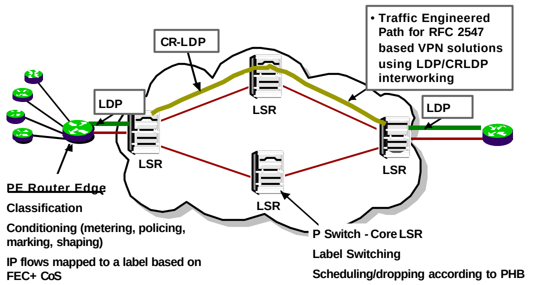
Example: MPLS End-to-End COS & QOS

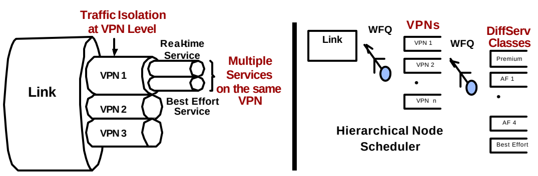


Example: Traffic Engineered Router Based VPNs



LDP/CRLDP Interworking Create Traffic Engineered Core

Example: Premium VPN Service



A Virtual Multi-Service Trunk Service:

- Exploits MPLS unique features: Per-LSP signaling, Label stacking, DiffServ support
- Requires hierarchical WFQ Scheduling for partitioning link bandwidth among customer VPNs, and for managing VPN BW among a customer traffic classes

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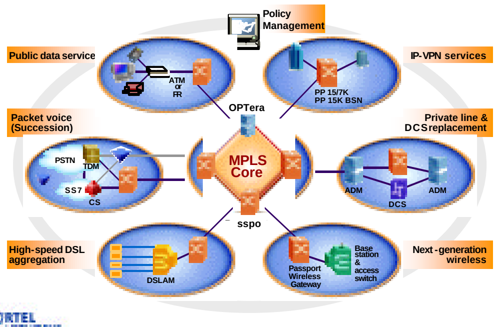
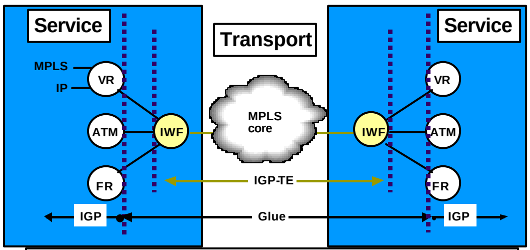
Multi-Service over MPLS

- **Motivation**
- **Architecture**
- **QoS Model**
- **ATM over MPLS Example**

Goal: MPLS-based Unified Networking



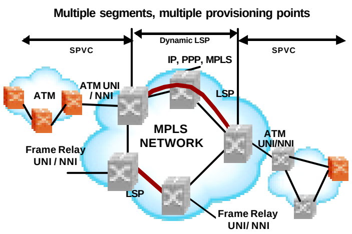
Architecture Concepts



Separate Transport from Service

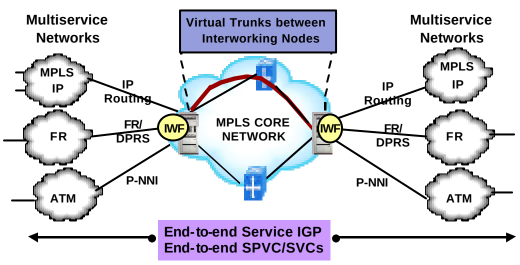
A **Transport Routing** system requires: an IGP-TE; isolation from Services
A **Service Routing** system requires: an IGP outwards; "Glue"

MPLS LER Nailed Up Services



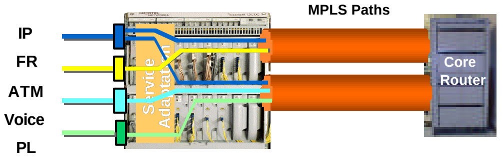
- Unified MPLS Core network infrastructure
- Layer 2 services adapted to the MPLS core at the edge of the network
- Support IP, PPP, Frame Relay, ATM, MPLS, and CES services

Network Interworking



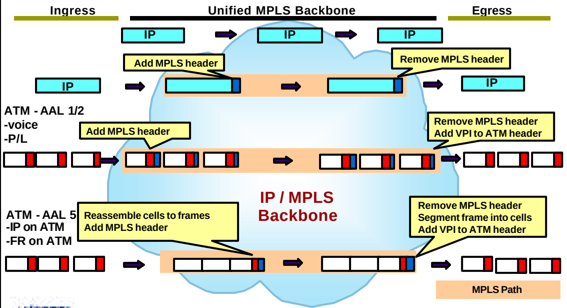
Creates a smooth evolution path for existing switched services to an MPLS core.

Multiservice Core Adaptation

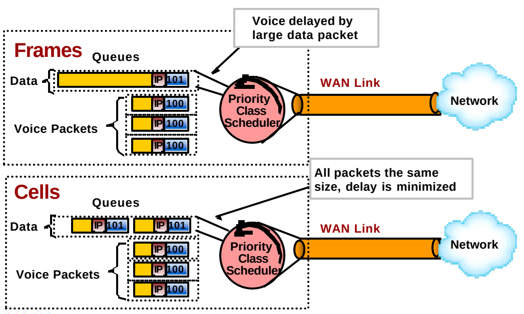


- Standard multi-service UNI and NNI capabilities
- Adaptation of existing nailed-up and switched services to MPLS/Packet Core
- Provide a range of QoS and CoS service capabilities
- Support flexible and scalable network evolution

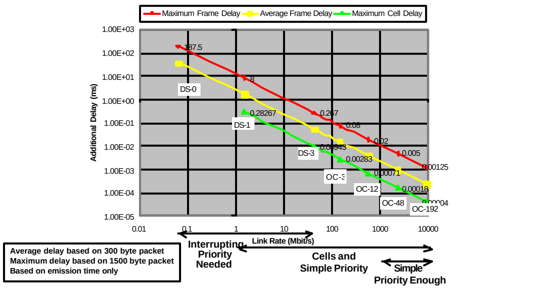
Packet Mapping into IP/MPLS Backbone



Link Layer Delay Considerations



Frame vs Cell Delay



Cellification of frames no longer needed at rates >OC12

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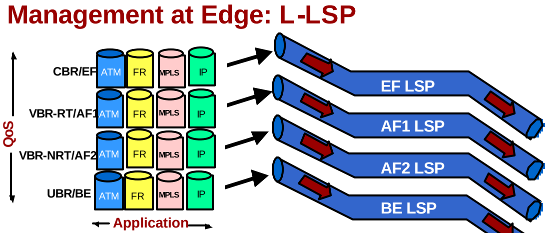
Multi-Service Resource Management at Edge: L-LSP



Extend the MPLS Bandwidth Management Pools model to multi-service resource management

Provide the option of partitioning or sharing the LSP tunnel bandwidth by service/application

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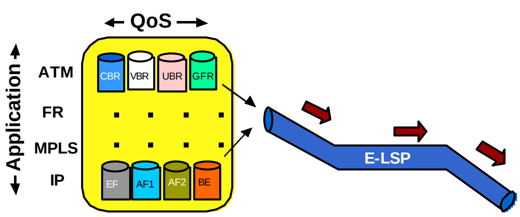
MPLS Multi-Service Resource Management at Edge: E-LSP



Provides the option of partitioning or sharing the E-LSP tunnel bandwidth by application and/or QoS

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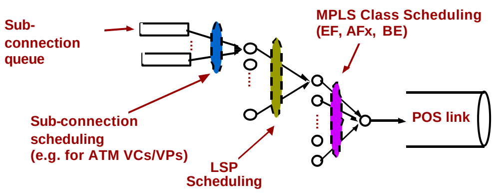
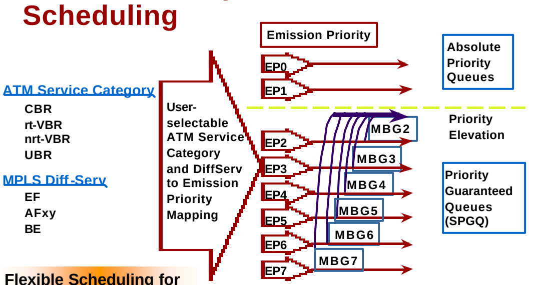
MPLS Edge Node Scheduling



Weighted Fair Queuing scheduling is performed at the following levels:

- **Class**, for guaranteeing service/class quality and starvation avoidance
- **LSP**, for weighted fairness, segregation, and shaping among LSPs
- **Subconnection**, for fairness between individual service connections

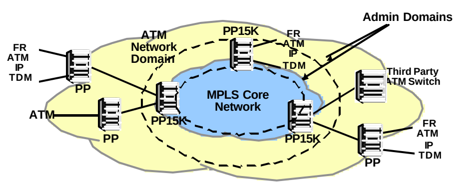
Multi-Service QoS Scheduling



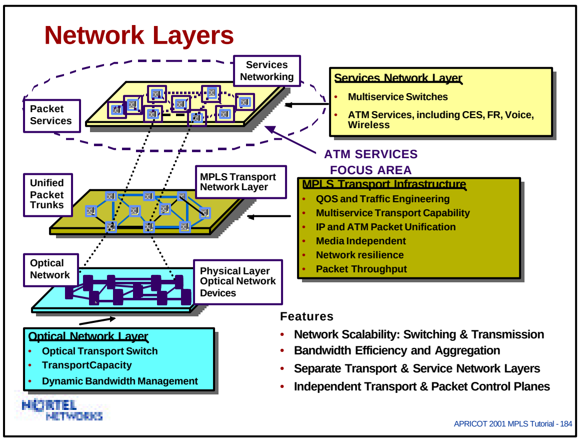
Flexible Scheduling for ATM and IP Traffic

MBG = Minimum Bandwidth Guarantee
EP = Scheduler Emission Priority

ATM Networking Over MPLS: Architectural Objectives



- Multiservice networking over an MPLS core network
- Scalability: switching capacity, performance & networking dimensions
- ATM networking equivalency - end-to-end quality of service guarantees
- Network interoperability with core and access switches
- Network resiliency and restoration
- Efficient utilization of network resources
- Support of multiple administrative domains


Network Layers
Services Networking
Packet Services
Services Network Layer
Multiservice Switches
ATM Services, including CES, FR, Voice, Wireless
ATM SERVICES FOCUS AREA
Unified Packet Trunks
MPLS Transport Network Layer
MPLS Transport Infrastructure
QOS and Traffic Engineering
Multiservice Transport Capability
IP and ATM Packet Unification
Media Independent
Network resilience
Packet Throughput
Optical Network
Physical Layer Optical Network Devices
Optical Network Layer
Optical Transport Switch
TransportCapacity
Dynamic Bandwidth Management
Features
Network Scalability: Switching & Transmission
Bandwidth Efficiency and Aggregation
Separate Transport & Service Network Layers
Independent Transport & Packet Control Planes
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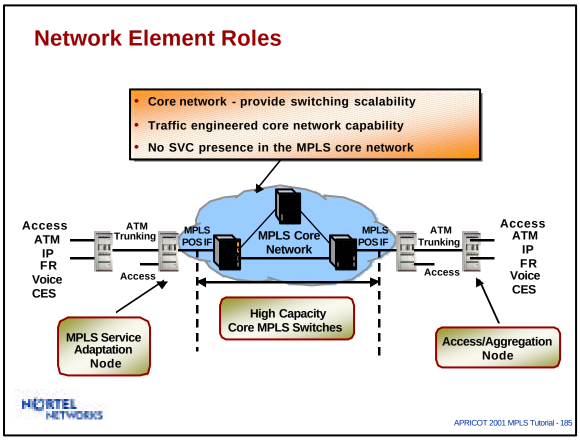
Network Element Roles
Core network - provide switching scalability
Traffic engineered core network capability
No SVC presence in the MPLS core network
Access ATM IP FR Voice CES
ATM Trunking
Access
MPLS POS IF
MPLS Core Network
MPLS POS IF
ATM Trunking
Access
Access ATM IP FR Voice CES
MPLS Service Adaptation Node
High Capacity Core MPLS Switches
Access/Aggregation Node
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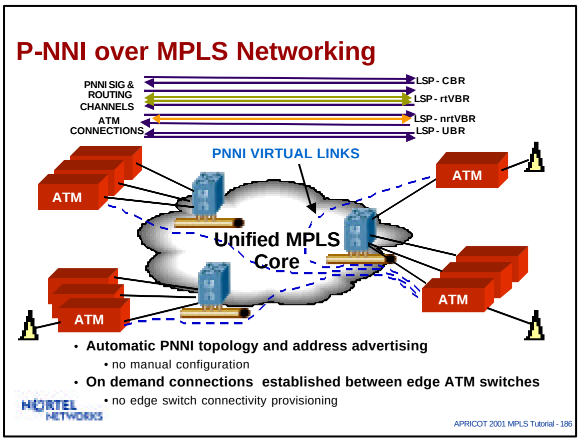
P-NNI over MPLS Networking
PNNI SIG & ROUTING CHANNELS
ATM CONNECTIONS
LSP - CBR
LSP - rtVBR
LSP - nrtVBR
LSP - UBR
PNNI VIRTUAL LINKS
ATM
ATM
Unified MPLS Core
ATM
ATM
Automatic PNNI topology and address advertising
no manual configuration
On demand connections established between edge ATM switches
no edge switch connectivity provisioning
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Example of ATM/ LSP Mapping

ATM SC	CLP	DiffServ PHB	PSC (L-LSP)	EXP Bits (L-LSP)	EXP Bits (E-LSP)
CBR	0/1	EF	EF	000	101
RT	0	AF11	AF1x	000	010
RT	1	AF12	AF1x	001	110
NRT	0	AF21	AF2x	000	111
NRT	1	AF22	AF2x	001	000
UBR	0/1	CS0	CS0	000	001

- L-LSP: Per Hop Scheduling Class (PSC) is signaled for each LSP. EXP mapping is fixed and used to indicate Discard Priority
- E-LSP: EXP Bits carry the full PHB info (PSC + Discard Priority). Mapping of PHB to EXP Bits is signaled or configured per LSP

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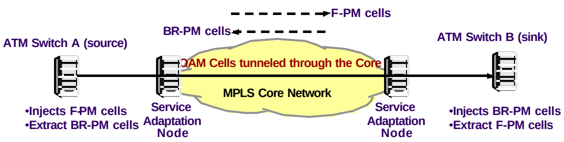
ATM Service Equivalency



Example: CLR Computation Using OAM PM Cells

- The network meets ATM end-to-end SLAs for Cell Loss Ratio (CLR), delay and delay variance:
  - Through a combination of Nodal Access & Core Traffic Management features and P-NNI QoS routing
- ATM SLAs can be verified using end-to-end Performance Management (PM) cells

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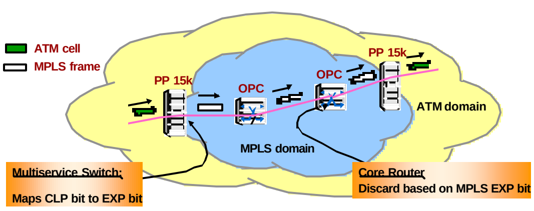
CLP Feature Support



- Essential feature for meeting service quality for guaranteed traffic
- CLP bit is set by ATM/FR policer at the Access UNI interface
- Both the Multiservice Switch and Core Router use the CLP information (mapped to MPLS EXP Bits) for discard priority differentiation

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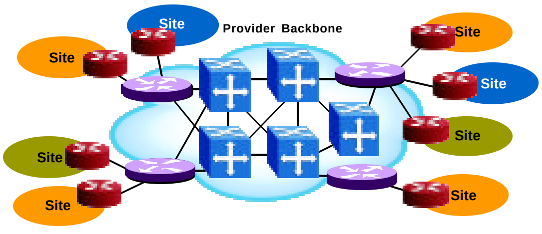
Multi-Service over MPLS Summary

- MPLS is the unified network core for all services
- MPLS enables sharing the network resources for all legacy and emerging services
- The architecture meets the requirements of existing services, and offers a smooth network evolution
- Nortel Networks is leading the drive for multi-service networking over MPLS

Tutorial outline

- Basic concepts
- Applications Overview
- Data Plane
- Control Plane
- MPLS and QoS
- Multi-Service over MPLS
- **MPLS and VPNs**
- MPLS and ASON
- Summary

What is a VPN?



VPN: Virtual Private Network
- a set of sites interconnected via a provider backbone

There are many VPN types …

- **L2 VPNs**
  - X.25 CUGS
  - Frame Relay
  - ATM
- **IP VPN Types (RFC 2764)**
  - Virtual Leased Lines (VLL)
  - Virtual Private Routed Network (VPRN)
  - Virtual Private Dial Networks (VPDN)
  - Virtual Private LAN Segment (VPLS)
- **Types of Tunnels**
  - L2
  - IP
  - IPSec
  - MPLS

We are only going to discuss MPLS-based VPNs

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Why MPLS tunnels?

- **MPLS is an efficient tunnel technology**
- **MPLS is IP centric**
- **MPLS is L2 agnostic**
- **MPLS LSPs are connection oriented**
- **MPLS LSPs can be nested inside one another**
- **MPLS offers traffic engineering**

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MPLS VPNs still in flux

- **No agreed-to standard for MPLS-based VPNs**
- **Here we present two proposals which are being developed and deployed…**

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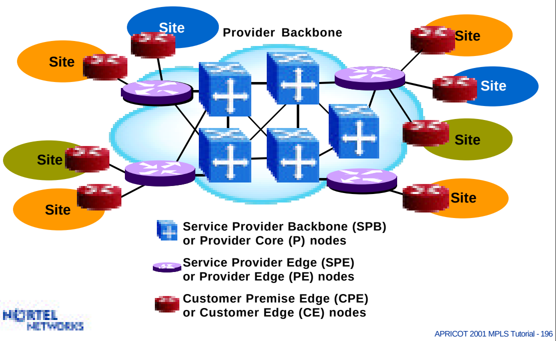
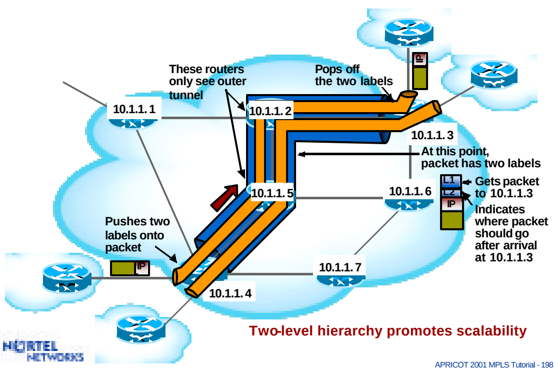
Two competing sets of terms



Two parts to each proposal

- **Data Transport**
  - how the data packets are transported from one site to another
  - this part the same between the two proposals
- **Routing Info Distribution**
  - how routing information is transported from one site to another
  - here the two proposals differ

Data transport

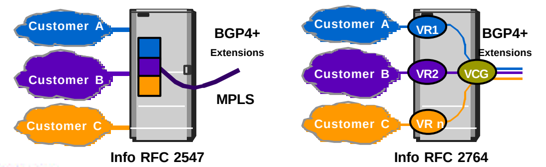


Two-level hierarchy promotes scalability

Routing info distribution

Method 1:
Multiple indexed tables in a single switch
- one BGP4 process with extensions for VPNs
- standard IP routing to customer (no OSPF)
- extended BGP4 routing into the core network
- hierarchical MPLS routing required in the core network

Method 2:
Virtual routers in a single switch
- each instance dedicated to a single customer with separate routing and forwarding tables
- standard IP routing to customer
- standard IP routing in the core network
- Core can be ATM, pure IP, or MPLS



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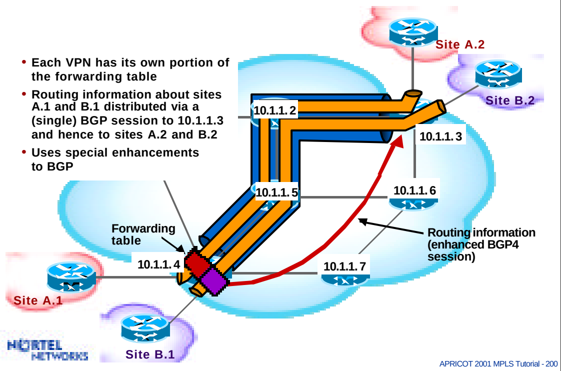
Method 1: BGP/MPLS VPNs

- Each VPN has its own portion of the forwarding table
- Routing information about sites A.1 and B.1 distributed via a (single) BGP session to 10.1.1.3 and hence to sites A.2 and B.2
- Uses special enhancements to BGP



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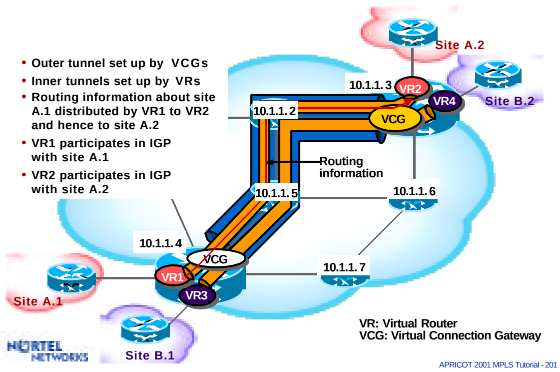
Method 2: Virtual Router VPNs

- Outer tunnel set up by VCGs
- Inner tunnels set up by VRs
- Routing information about site A.1 distributed by VR1 to VR2 and hence to site A.2
- VR1 participates in IGP with site A.1
- VR2 participates in IGP with site A.2



VR: Virtual Router
VCG: Virtual Connection Gateway

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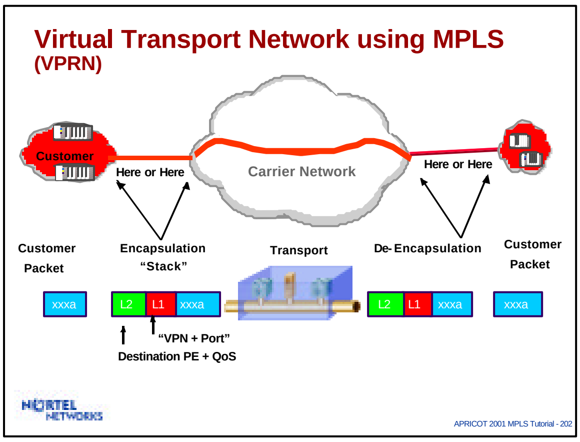
Virtual Transport Network using MPLS
(VPRN)
Customer
Here or Here
Carrier Network
Here or Here
Customer
Packet
Encapsulation
“Stack”
Transport
De-Encapsulation
Customer
Packet
xxxa
L2
L1
xxxa
L2
L1
xxxa
xxxa
“VPN + Port”
Destination PE + QoS
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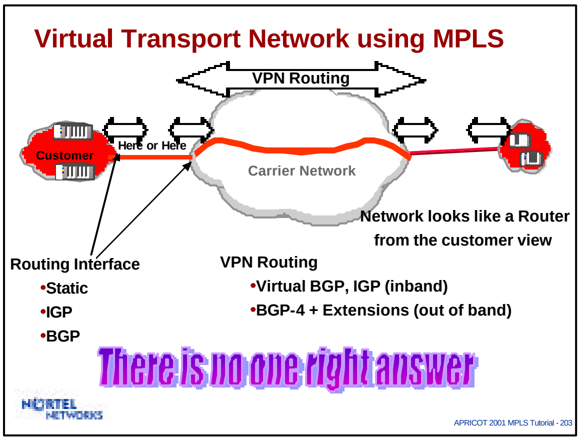
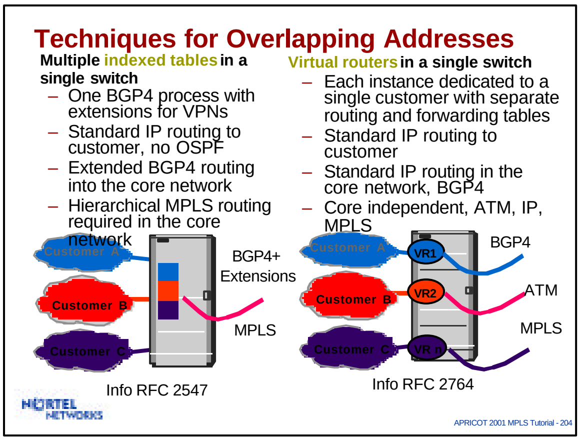

Virtual Transport Network using MPLS
VPN Routing
Customer
Here or Here
Carrier Network
Network looks like a Router
from the customer view
Routing Interface
•Static
•IGP
•BGP
VPN Routing
•Virtual BGP, IGP (inband)
•BGP-4 + Extensions (out of band)
There is no one right answer
APRICOT 2001 MPLS Tutorial - 203


Techniques for Overlapping Addresses
Multiple indexed tables in a single switch
– One BGP4 process with extensions for VPNs
– Standard IP routing to customer, no OSPF
– Extended BGP4 routing into the core network
– Hierarchical MPLS routing required in the core network
Virtual routers in a single switch
– Each instance dedicated to a single customer with separate routing and forwarding tables
– Standard IP routing to customer
– Standard IP routing in the core network, BGP4
– Core independent, ATM, IP, MPLS
Customer A
Customer B
Customer C
BGP4+
Extensions
MPLS
Info RFC 2547
VR1
VR2
BGP4
ATM
MPLS
Info RFC 2764
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Virtual Transport Network MPLS Label Distribution

Implicit:

LDP is the MPLS protocol for implicitly assigning labels based upon the 'hop by hop' path chosen by the Service Provider's IGP in the base netw…

Best Effort

Explicit traffic placement:

CR-LDP or Extended RSVP can be used to place a LSP through designated core LSR's and assign the corresponding labels to the VPN traffic

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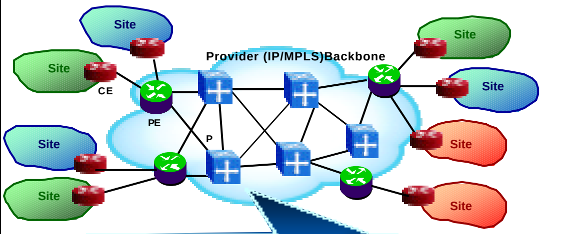
MPLS VPN Architecture



- Set of "sites" attached to a common network ("backbone") through Provider Edge (PE) routers
- VPN: A subsets of the set of sites
- Two sites have IP connectivity over the backbone only if they belong to the same VPN
- A site may belong to more than one VPN

CE: Customer Edge device
PE: Provider Edge Router
P: Provider (Backbone Router)

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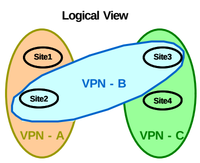
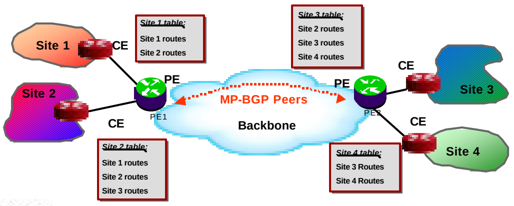
Overlapping VPNs

A site receives routes only from VPN member sites.

Logical View





Note: There is no connectivity between sites not sharing any VPNs, e.g. Site 2 and Site 4, etc.

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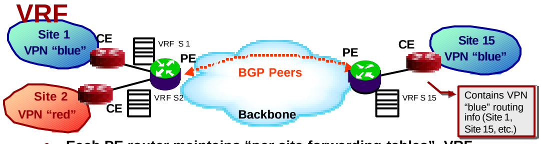
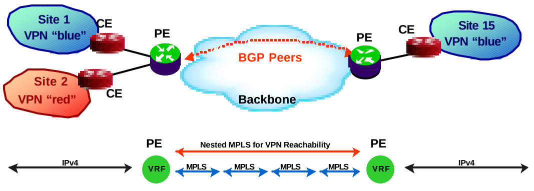
Virtual Routing and Forwarding Tables, VRF



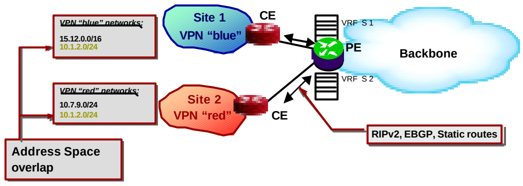
- **Each PE router maintains "per-site forwarding tables", VRF**
  - Every site to which the PE router is attached is associated with a VRF
  - When an IP (v4) packet arrives from a site (CE router), its destination address is looked up on the VRF associated with the site (association normally through interface)
- **Key Considerations:**
  - How to determine VPN membership (what route goes into what VRF)
  - How to distribute VPN membership to relevant VRFs

VPN Information Distribution



- **IPv4 between CE and PE**
- **MPLS for Backbone connectivity**
  - IS-IS, OSPF
  - LDP, RSVP, CR-LDP
- **Nested MPLS for VPN connectivity**
  - BGP-4
  - non-IPv4 addresses (more about that later)

CE-to-PE Route Exchange



- **PEs need to know what networks are reachable on each site**
  - Routes learned from a site will be placed on the VRF table for that site
  - Address space overlap between VPNs is allowed because routes go to different VRFs
- **PEs must informCEs of other routes in the same VPN**
  - Options: RIP-2, External BGP (EBGP), static routes. (OSPF: later)
  - The per-VPN routing tables are not very large

Dealing with Overlapping Address Space

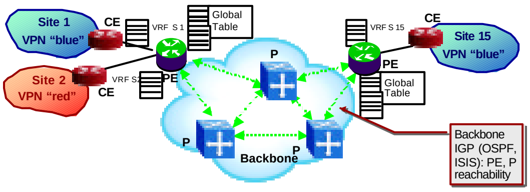
VPN IPv4 Address

- **BGP limitation: One route to a given address prefix**
- **Each VPN could have independent address space:**
  - same IPv4 Prefix could be repeated in several VPNs
  - we need to allow BGP to install and distribute multiple routes to a single IPv4 address prefix.
- **Enlarge IPv4 Addressing: New Address Family (AF) and BGP Multiprotocol Extensions.**

Route Distinguisher

- **VPN-IPv4 Address: 12 bytes:**
  - 8-byte “Route Distinguisher”
  - 4-byte IPv4 address
- **Route Distinguisher (RD) is not a VPN-ID:**
  - Does not impose semantics
  - Route Distinguisher does not identify a VPN.
- **Only purpose of RD: Allow BGP to create distinct routes to a common IPv4 address prefix**

Backbone Routing



- **IGP routing tables are present in PE routers as well as in P routers**
  - Populated by backbone IGP protocols (e.g. OSPF, ISIS)
  - Entries are “plain” IPv4 routes (as opposed to “VPN-IPv4” addresses)
  - Contains info on how to reach other PEs and P routers
  - Used by backbone MPLS LDP and IBGP
  - May include routes received from Internet peers, if connected to Internet
- **Does not contain any VPN related info**

VPN Routing and Forwarding, Nested MPLS

- **VPN MPLS**
  - Label distributed between PEs through BGP
  - Inner label in stack. Also called VPN label
  - Label Distribution Protocol (LDP): BGP
  - Involves only PE routers
- **Core MPLS:**
  - Used to connect PE-backbone-PE
  - Outer label in stack. Also called IGP label
  - Involves PE and P routers
  - LDP, CR-LDP, RSVP, can be anything

VPN-IPv4 Route Distribution

- **Key Attribute: Route Target**
  - VPN-IPv4 routes associated with one or more Route Targets
  - A route can have only one RD, but it can have multiple RTs.
- **Key Attribute: Site of Origin**
  - Identifies the site from which the PE router learned the route.
  - Unique for a given site, even if it is multi-homed.
  - Helps prevent routing loops.
- **Matching Route Targets**
  - Export targets: RTs associated with a route
  - Import targets: RTs associated with a VRF

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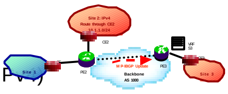
VPN BGP Update



- **Sending an Update**
  - VPN-IPv4 Address (RD + IPv4)
    - Sent using Multiprotocol Extensions
    - Includes Next Hop (PE that sends update)
  - Extended Community Attributes
    - Route Target (who can use this route)
    - Site of Origin (site originating this route)
    - Other standard BGP attributes (community, local preferences, etc.)
  - MPLS Label ("BGP label")
    - Identify the outgoing Interface
- **Receiving an Update**
  - Match Routes' RTs to its list of import RTs
  - Translate VPN-IPv4 address to IPv4
    - Puts IPv4 address in the Virtual Forwarding table for the associated site
  - Advertise routes to the associated site
    - Propagates the route to the site via CE to PE protocol, RIP or BGP
    - The CE is not aware, nor concerned with how the route was installed at PE

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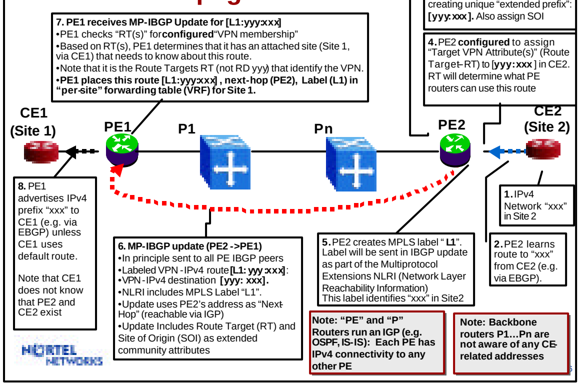
Route Propagation Overview



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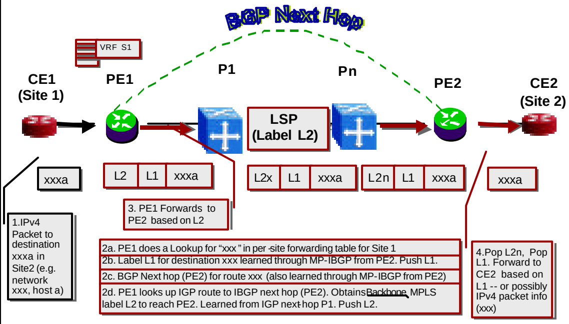
Packet Forwarding Overview

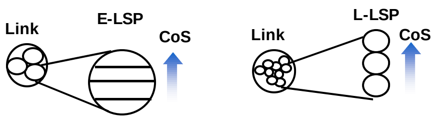


VPN Traffic Engineering Models

- **There are two models:**
  - Between two end points i.e. On a pair-wise basis between edge routers
  - Between an origin and a set of destinations
- **The two models can be abstracted into**
  - Pipes: Provides performance guarantee for traffic between a <src, dst> pair. It is very similar to a leased line.
  - Hoses: Provides performance guarantee between an origin and a set of destinations both inbound and outbound

MPLS Class of Service (CoS)

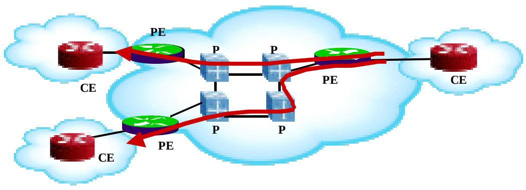
- **MPLS provides CoS**
  - This is achieved by using L-LSP's or E-LSP's
  - L-LSP's are used when a separate label is used to identify each CoS within a VPN
  - E-LSP is used when the EXP bits in the labels are used to identify the CoS within a VPN



MPLS LSP Cross Sections

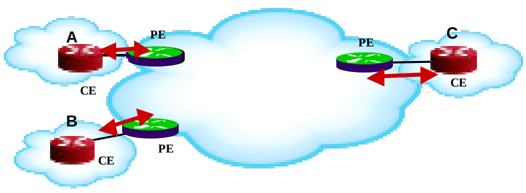
PIPE Example

- **Pipe Model is analogous to the Layer 2 Model**
  – Offers ability to control End to End QoS



Hose Example

- **Hose Model**
  – Traffic in the provider cloud to satisfy A+B traffic to C



Comparing the models

Pipe Model

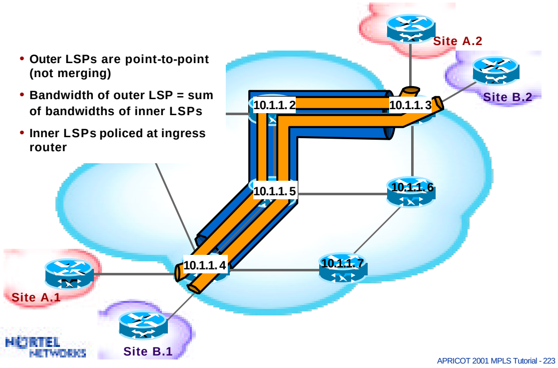
- **Provides QoS guarantees between each pair of customer sites**
- **Good when one wants hard QoS guarantees between two sites**
- **Similar to a leased line**

Hose Model

- **Provides QoS guarantees between a site and all other sites collectively**
- **Good when one doesn't know the matrix of traffic usage between sites**
- **For each site, specify:**
  – **Inbound Committed Rate (ICR)**
  – **Outbound Committed Rate (OCR)**

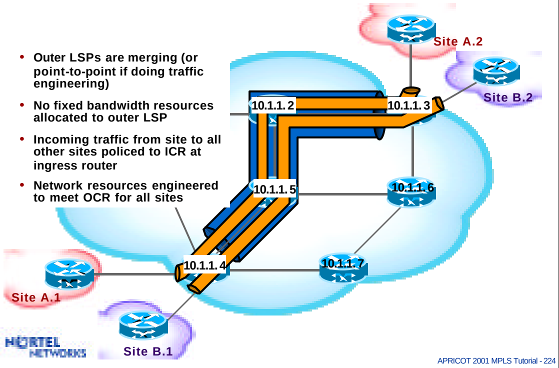
Pipe model implementation

- Outer LSPs are point-to-point (not merging)
- Bandwidth of outer LSP = sum of bandwidths of inner LSPs
- Inner LSPs policed at ingress router



Hose model implementation

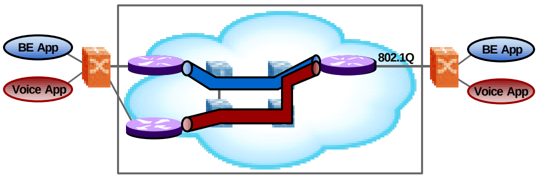
- Outer LSPs are merging (or point-to-point if doing traffic engineering)
- No fixed bandwidth resources allocated to outer LSP
- Incoming traffic from site to all other sites policed to ICR at ingress router
- Network resources engineered to meet OCR for all sites



More sophisticated QoS

- **It is possible to mix the pipe and hose models**
  - point-to-point QoS between certain pairs of sites
  - aggregate QoS for the rest of the VPN
- **Can also provide different classes of service**
- **For example:**
  - service provider offers 5 classes of service
  - VPN customer decides what subset of these classes he/she wishes to purchase
- **Can use Diff-Serv with MPLS to offer service classes**

Example of CoS in a VPN



- The Best Effort traffic (blue) and the voice traffic (red) take divergent paths on the network
- The red path is optimized through traffic engineering for low latency applications

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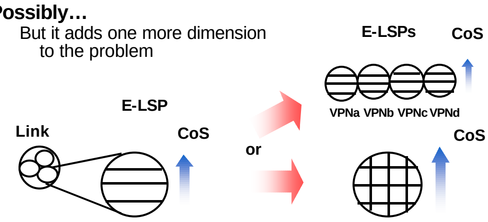
Does MPLS TE + MPLS VPN = VPN TE ?

Possibly…

But it adds one more dimension to the problem



MPLS LSP Cross Section
•TE between LSP
•CoS within LSP

MPLS LSP Cross Section
•TE between LSP
•CoS within LSP
•VPNs across a CoS

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MPLS IP VPN TE Benefits ISP Perspective

- **Optimizes network resource usage**
- **Traffic Engineering features to provide advanced services**
- **Dedicated Bandwidth for VPNs between two sites**
  - VLL like service
- **Setup LSPs for carrying aggregated premium traffic**
- **Dynamically change bandwidth on the LSPs**
  - draft-ietf-mpls-crlsp-modify-00.txt

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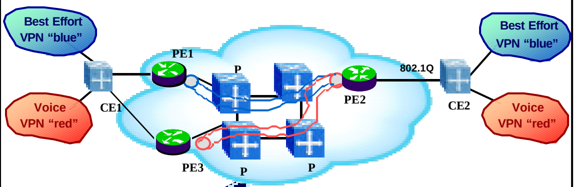
Using Traffic Engineered Tunnels for VPNs



- The Best Effort VPN (blue) and the voice VPN (red) take divergent paths on the network
- The red path is optimized through traffic engineering for low latency applications

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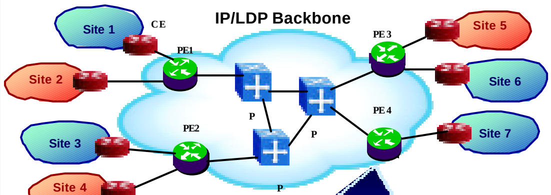
Non-disruptive VPN Service Configuration



- Adding Site 8
- No import target for Red VPN at PE4
- IPv4-VPN Red routes are dropped at PE4
- Add Red VPN to PE-4 without resetting iBGP Peers

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What protocol should we use?

LDP?

- Automatic tunnel setup
- Merging LSPs
  ® more scalable
- No traffic engineering or QoS

CR-LDP / RSVP-TE?

- Configured tunnel setup
- Point-to-point LSPs
  ® less scalable
- Provides traffic engineering and QoS

Could use a combination

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Tutorial outline

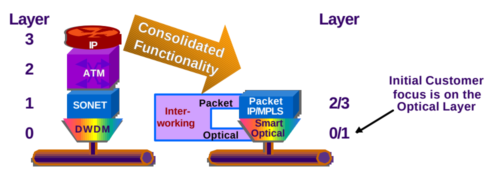
- Basic concepts
- Applications Overview
- Data Plane
- Control Plane
- MPLS and QoS
- Multi-Service over MPLS
- MPLS and VPNs
- **MPLS and ASON**
- Summary

Smart Optical Layer Evolution

Evolving from Static Connectivity to a Dynamic Infrastructure and Service Layer

What do we need to make it "Smart"?
- Agile Optical Layer
- Automatic Switched Optical Network (ASON)

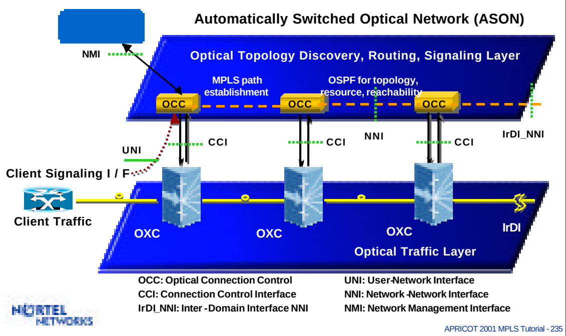
Smart Packet/Optical Interworking



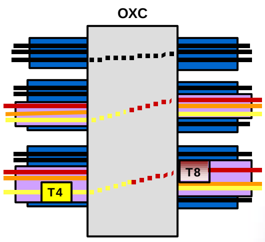
Drivers
- Traffic Growth
- Multi-Service
- Simplicity
- Service Velocity
- Network Cost

Challenges
- Robustness and Support for QoS
- Policy Based Networking
- Bandwidth Management Optimization
- Flexible Restoration

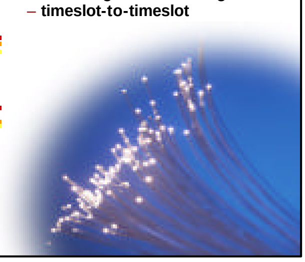
The Intelligent Optical Network



Optical cross-connect switch



- **Can cross-connect:**
  - **fiber-to-fiber**
  - **wavelength-to-wavelength**
  - **timeslot-to-timeslot**



Treat these as labels

- **Using MPLS, we can think of each of these as a label**
  - Fiber number N in the bundle (N is the label)
  - Wavelength λ on the fiber (λ is the label)
  - Timeslot T on the fiber (T is the label)
- **Changing N, λ, or T going through an optical switch is thus a label swap**
- **Can use CR-LDP / RSVP-TE to set up the cross-connects**

ASON Building Block Development

Architectural Component	Standards Activity	Standards Forums
ASON Architecture	Framework and Architecture Documents	• Architecture and carrier service requirements are being defined in the ITU. • In addition US activity is coordinated via T1X1 .
UNI	LDP	• Carrier service requirements driven via OIF • Detailed protocol work within IETF
NNI	CR-LDP OSPF OSPF, ISIS	• Requirements driven via OIF • Detailed protocol work within IETF
CCI	GSMP	• Requirements driven via Multi-Service Switching Forum (MSF) • Detailed protocol work within IETF
IrDI	Detailed work to be commenced	• Will be based on UNI with possible extensions for routing information exchange
NMI	Detailed work to be commenced	• SNMP MIBs to be defined. • Higher level managed capabilities to be based on existing management paradigms such as CORBA.

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MPLS Applied to Optical Networks (UNI,NNI)

- **Function Supported**
  - MPLS is used to define paths through the optical network. The label-space is being generalized to be able to describe lightpath granularities (including wavebands and wavelengths; this generalization also supports SDH/SONET and spatial switching)
- **Benefits of MPLS**
  - Facilitates support of QoS
  - Facilitates traffic engineering
  - Provides common methodology for path establishment for packet and optical layers
- **Nortel Networks Role in this Work**
  - Nortel has participated actively in the development of 25+ IETF Internet Drafts dealing with MPLS and LDP
  - Nortel is co-editor of the Generalized MPLS IETF Internet Draft

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LDP and CR-LDP Applied to Optical Networks (Signaling)

- **Function Supported**
  - LDP is used to distribute labels for the purpose of MPLS path establishment CR-LDP supports constraint based routing
- **Benefits of LDP, CR-LDP**
  - Scalable to 100,000+ nodes
  - CR-LDP is based on the premise that hard state is the best design approach for connection-oriented paths
  - Reliability and Flow Control via TCP
- **Nortel Networks Role in this Work**
  - Nortel has participated actively in the development of 25+ IETF Internet Drafts dealing with MPLS and LDP
  - Nortel is editor of the LDP Extensions for Optical UNI IETF Internet Draft
  - Nortel is author of an IETF Internet Draft on Extension for Interworking CR-LDP and RSVP-TE

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OSPF/ISIS Usage in Optical Networks (Routing)

- **Function Supported**
  - OSPF is used to exchange routing information between IP devices in the same domain, (i.e. it is an IGP). Extensions are proposed to support link state advertisements (LSAs) in support of optical networks and traffic engineering. Extensions include support for definition of shared risk link groups (SRLGs) and link protection. In addition proxy control capabilities are defined.
- **Benefits of OSPF/ISIS**
  - Robust routing protocol used to establish optical path
  - Support of route selection based on traffic and QoS parameters
  - Provides a common methodology for optical path establishment and IP routing
- **Nortel Networks Role in this Work**
  - Nortel is participating actively in the development of 6+ IETF Internet Drafts dealing with OSPF and OSPF/ISIS extensions to handle traffic engineering and optical support

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Important Features of MPLS

- **Runs over many different Layer 2 technologies**
  - Ethernet, PoS, ATM, FR, Optical
- **LSPs can be point-to-point or merging**
  - Point-to-point LSPs allow explicit routing and QoS reservations
  - Merging LSPs reduce number of LSPs required
- **LSPs can nest inside other LSPs**
  - Provides scalability; core routers know only about outermost LSP

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Setting up LSPs

- **LDP**
  - Merging LSPs that follow the shortest path
  - No QoS
- **CR-LDP or RSVP-TE**
  - Point-to-point LSPs
  - Explicit route, QoS reservations, Preemption, Make-before-Break
- **Constraint Based Routing (eg. OSPF or ISIS)**
  - Can enhance with TE extensions to do online path selection

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Important Applications of MPLS

- **Traffic Engineering**
  - Use point-to-point LSPs to move traffic away from congested links onto under-utilized links.
- **Replace BGP on interior routers**
  - Use mesh of LSPs to avoid the need to run BGP on interior routers.
- **Integrate IP and ATM**
  - Use MPLS to set up merging LSPs through ATM switches, thus avoiding N^2 and N^3 problems.
- **Virtual Private Networks**
  - Use LSPs as tunnels to provide private connections through a public network
- **Automatically Switched Optical Networks**
  - Use MPLS signaling rather than manual configuration to set up cross-connects inside optical switches.

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MPLS Resources

- **Nortel's MPLS website**
  - http://www.nortelnetworks.com/mpls
  - Contains white papers, product information, and freely-available source code
- **MPLS Resource Center**
  - http://www.mplsrc.com/
  - A commercial web site offering MPLS information. Good place to look for books, articles, press releases, etc.
- **Great MPLS Book**
  - Bruce Davie and Yakov Rekhter, *"MPLS Technology and Applications"*
  - Morgan Kaufmann, 2000

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MPLS Resources

- **MPLS Working Group at the IETF**
  - http://www.ietf.org/html.charters/mpls-charter.html
  - This is group that does all the work on MPLS. Anyone can subscribe to the mailing list and read the documents.
- **MPLS WG mailing list archive**
  - http://cell.onecall.net/cell-relay/archives/mpls/mpls.index.html
  - Here you can read earlier discussions on the mailing list.
- **Archive of internet-drafts related to MPLS**
  - http://infonet.aist-nara.ac.jp/member/nori-d/mlr/
  - Internet-drafts are deleted from the IETF site after 6 months or when a new version comes out. Here you can find the old versions, as well as other older goodies.
- **Free Linux implementation: University of Wisconsin**
  - ftp://nero.doit.wisc.edu/pub/mpls/

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MPLS WG Documents

- **The MPLS Working Group has created lots of documents. Here are some good ones to start with.**
  - "Multiprotocol Label Switching Architecture"
    - Gives complete and precise definitions of basic MPLS concepts. Good document to read first..
  - "MPLS Label Stack Encodings"
    - Describes the format of the MPLS label stack. Note that for some formats (e.g., ATM and FR), this information needs to be supplemented with other documents.
  - "LDP Specification"
    - The protocol specification for LDP.
  - "Constraint-Based LSP Setup using LDP"
    - The protocol specification for CR-LDP.
  - "RSVP-TE: Extensions to RSVP for LSP Tunnels"
    - The protocol specification for RSVP-TE.
- **These documents are available on the MPLS WG web page under "Internet Drafts" and "Request for Comments".**

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MPLS Standards Update

- **LDP/CR-LDP RFCs coming soon**
  - http://www.ietf.org/internet-drafts/draft-ietf-mpls-ldp-10.txt
  - http://www.ietf.org/internet-drafts/draft-ietf-mpls-cr-ldp-04.txt
- **CR-LDP Modify -- Informational RFC**
  - http://www.ietf.org/internet-drafts/draft-ietf-mpls-crlsp-modify-01.txt
- **CR-LDP Feedback -- past WG last call**
  - http://www.ietf.org/internet-drafts/draft-ietf-mpls-te-feed-01.txt
- **MPLS LDP Query**
  - http://www.ietf.org/internet-drafts/draft-paraschiv-mpls-lsp-query-00.txt
- **Extensions for support of Differentiated Services Traffic Engineering**
  - http://www.ietf.org/internet-drafts/draft-lefaucheur-diff-te-ext-00.txt
- **COPS Usage for MPLS/Traffic Engineering**
  - http://www.ietf.org/internet-drafts/draft-franr-mpls-cops-00.txt

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MPLS Standards Update

- Network based IP VPN Architecture Using Virtual Routers
  - http://www.ietf.org/internet-drafts/draft-ouldbrahim-vpn-vr-01.txt
- BGP/VPN: VPN Information Discovery for Network-based VPNs
  - http://www.ietf.org/internet-drafts/draft-ouldbrahim-bgp-vpn-00.txt
- Framework for MPLS Based Recovery
- Fault Tolerance for LDP and CR-LDP
- FLIP: draft-sandiick-flip-00.txt
- Extensions to CR-LDP and RSVP-TE for setup of pre-established recovery tunnels
  - http://www.ietf.org/internet-drafts/draft-hellstrand-mpls-recovery-merge-00.txt

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MPLS Standards Update

- IP over Optical Networks: A Framework
- MPLS Optical/Switching Signaling
  - http://www.ietf.org/internet-drafts/draft-ashwood-generalized-mpls-signaling-00.txt
- OSPF Extensions in Support of MPL(ambda)S
  - http://www.ietf.org/internet-drafts/draft-kompella-ospf-ompls-extensions-00.txt
- IS-IS Extensions in Support of MPL(ambda)S
  - http://www.ietf.org/internet-drafts/draft-kompella-isis-ompls-extensions-00.txt
- A User-Network Interface (UNI) for re-Configurable Optical Networks
  - http://www.ietf.org/internet-drafts/draft-aboulmagd-mpls-ldp-optical-uni-00.txt

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