Multi-Protocol Label Switching (MPLS)

Internet Routing + Label Switching

* Some materials come from Cisco.com
Learning Outcomes

• know the motivation/objectives of MPLS
• know the challenge and basic ideas of MPLS
• know how MPLS works
• know how to assign labels (globally vs. locally)
• know how to forward IP packets and switch labels in MPLS domain
• know how to allocate and distribute labels
• know the difference between IP routing and MPLS routing and how they work
• know how MPLS-VPN works
Challenge

How to design routing and switching in the core network of the Internet with the following objectives:

• Handle a vast volume of traffic (Scalability)
• Provide different qualities of service (QoS)
• Load-balance the traffic in the core network (Traffic Engineering)
Outline

• *Problems on the Internet*
• Solution to the problems: MPLS
• How MPLS solves those problems
• How MPLS works
  – Packet forwarding & Label Switching
  – Label Distribution
  – Label Allocation Schemes
• Examples for IP routing vs. MPLS routing
• MPLS-VPN
Problems on the Internet (1)

Problem 1:

Normal IP forwarding is slow

=> Not scalable and not practical in the Internet core

Procedure for normal IP forwarding
1. Read the destination address
2. Perform longest-match table lookup (time consuming!!)
3. Find the next hop to forward
Problems on the Internet (2)

Problem 2:

Difficult to provide quality of service (QoS) because

– packets for the same source-destination pair may go through different paths

– difficult to keep track which path the traffic go through and hence difficult to reserve resources (e.g. bandwidth and buffer) along that path
Packets flow in the Internet
Problems on the Internet (3)

Problem 3:

No mechanism to control traffic, leading to

– unbalanced traffic distribution, hence causing
  • unnecessary congestion in some areas but
  • under-utilization in some other areas

– the danger of route oscillation – e.g. the “fish” problem
The “fish” problem (1)
The “fish” problem (2)
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Solution

Multi-Protocol Label Switching (MPLS)
The basic ideas of MPLS

• Build a “mass transportation” system in the core of the Internet, giving the traffic with predefined paths (decided by a traffic engineering mechanism NOT by IP routing protocol)
• Group/Aggregate and label traffic-flows
• Forward packets with labels in the predefined paths
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Problems solved

**Problem 1:** Normal IP forwarding is slow

**Solution:** Packets forwarded with labels using exact-match table lookup

=> make packet forwarding faster
Problems solved

**Problem 2**: Difficult to provide QoS.

**Solution**: The traffic in a flow will follow a predefined path

⇒ enable to reserve the resources (e.g. bandwidth and buffer) along that path

⇒ make the provision of QoS much easier
Problems solved

**Problem 3:** Unbalanced traffic distribution and the danger of causing route oscillation

**Solution:** From packet-based routing to pre-determined flow-based routing

⇒ more control on how the traffic distribute in the network (traffic engineering)

⇒ load-balance traffic
Unbalanced Traffic Distribution (before)

Path for R2 to R3 traffic
Path for R1 to R3 traffic
under-utilized alternate path
Balanced Traffic Distribution (now!!)

Path for R2 to R3 traffic
Path for R1 to R3 traffic
Summary on Advantages of MPLS

• Increase scalability through
  – link-level **fast-forwarding** of IP-packets
  – flow aggregation

• Provide QoS

• Implement Traffic Engineering

• Build highly scaleable Virtual Private Networks (VPNs)

• Support multi-protocols: IP, ATM, frame relay
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How MPLS works

• An MPLS domain contains **MPLS-enabled IP router**, called **Label Switching Routers (LSRs)** – perform **label switching**

• A **Label Switched Path (LSP)** is set-up before packet transmission in MPLS domain

• An IP packet enters the MPLS domain via an **ingress** (edge) LSR which
  – Identify the **Forwarding Equivalency Class (FEC)** – the way to group IP packets in MPLS domain
  – Assign the **label** associated with the **FEC**

• With the label, the packet is forwarded to the next LSR along the LSP

• The packet leaves the MPLS domain via an **egress** (edge) LSR where its label removed
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Packet Forwarding & Label Switching

• At the core LSR, the label is used in an exact-match table lookup to identify
  – The next LSR in the LSP
  – The new label value
• The packet with the new label is forwarded to the next LSR
MPLS Packet Forwarding
Label (virtual circuit number) switching/changing

Why doesn’t a packet just keep the same label (VC number) on each of the links along a LSP?

1. Reduced complexity for setting up a LSP (more scalable)
2. Lower blocking probability
Reduced LSP-Setup Complexity

• Each link in the LSP can choose a VC number **independently** of what the other links in the LSP choose.
  – avoid the use of a complicated control algorithm => more scalable

• Only **adjacent switches** need to cooperate with each other.
  – reduce the number of message exchanges between the switches => more scalable
Lower Blocking Probability

• It is possible that each link has available VC number while there is **no common VC number** available in every link along the LSP.

• If VC number is not allowed to change from link to link, the connection will be **blocked** in this case.
Example: Blocking?

Assume that only two VC numbers are available in the network.

What happens if B wants to establish a connection with D?
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Label Distribution

- **Label Distribution Protocol (LDP)** is used to distribute the labels when LSP is setup.
- Egress router starts to distribute labels and passes them to its upstream LSRs.
- Each LSR
  - Receives outgoing label from downstream LSR.
  - Allocates and distributes incoming labels to upstream LSR.
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Label Allocation Schemes

- **Application flow**
  - End-to-end flow
  - Fine control but not scale well
- **Destination IP-prefix**
  - Aggregate flows destined to the same destination network
  - Scale better
  - Easy to implement due to the same information carried in IP routing protocols
- **Egress router**
  - Aggregate flows destined to the same egress router
  - Scale much better
  - Less control of individual traffic flows
Question

How to decide which label allocation scheme to be used?
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• *Examples for IP routing vs. MPLS routing*
• MPLS-VPN
IP Routing

- Distributing Routing Information (IP routing)
- Forwarding Packets (normal IP forwarding)
### IP Routing: Distributing Routing Information

#### Routing Updates (OSPF, RIP…)

<table>
<thead>
<tr>
<th>Address Prefix</th>
<th>I/F</th>
</tr>
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<tbody>
<tr>
<td>128.89</td>
<td>1</td>
</tr>
<tr>
<td>171.69</td>
<td>1</td>
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You Can Reach 128.89 and 171.69 thru Me

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You Can Reach 128.89 thru Me

128.89

0

128.89

0

171.69

You Can Reach 171.69 thru Me
IP Routing: Distributing Routing Information

- Interior gateway protocols, like Open Shortest Path First protocol (OSPF) or Routing Information Protocol (RIP), create, maintain and communicate routing tables that define how to get to a particular destination across a network.
- Each router advertises all the destinations that are reachable through its interfaces.
- Routers use this information to build their routing tables.
IP Routing: Forwarding Packets

Packets Forwarded Based on IP Address
IP Router: Forwarding Packets

• When a packet comes into a router, a look-up is done based on the IP address in the packet.
• If a match is obtained, the packet is forwarded out the appropriate interface.
• The packet follows the same process on a hop-by-hop base through the network until it reaches its destination.
MPLS Routing

• Distributing Routing Information (IP routing)
• Assigning Labels (label distribution protocol)
• Forwarding Packets (fast label switching)
• Label Sharing (flow aggregation)
### MPLS Routing: Distributing Routing Information

<table>
<thead>
<tr>
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</table>

Routing Updates (OSPF, RIP...)

- You Can Reach 128.89 and 171.69 thru Me
- You Can Reach 171.69 thru Me
- You Can Reach 128.89 thru Me
MPLS Routing: Distributing Routing Information

- What label switching does is to extend the forwarding table by adding a label field.
- One for the incoming label and one for the outgoing label.
- Note that the topology of the network is discovered using unmodified layer 3 protocols such as OSPF.
MPLS Routing: Assigning Labels

<table>
<thead>
<tr>
<th>In Label</th>
<th>Address Prefix</th>
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<tr>
<td>-</td>
<td>171.69</td>
<td>1</td>
<td>5</td>
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<tr>
<td>...</td>
<td>...</td>
<td>...</td>
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</tr>
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</table>

Use Label 4 for 128.89 and Use Label 5 for 171.69

Routing Updates (OSPF, RIP...)

Use Label 7 for 171.69

Use Label 9 for 128.89

128.89

171.69

0 128.89
MPLS Routing: Assigning Labels

• LDP is used to
  – Bind/link labels to paths/routes
  – distribute this information to each upstream neighbor of routers.
MPLS Routing: Forwarding Packets

**Ingress LSR Labels**

**IP Packet**

**Core LSR Forwards based on Label**

**Data**

### Table 1

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<th>Out Label</th>
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<tr>
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### Table 3

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<th>Out l’face</th>
<th>Out Label</th>
</tr>
</thead>
<tbody>
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<td>9</td>
<td>128.89</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

128.89.25.4 Data

Core LSR Forwards based on Label

128.89.25.4 Data

171.69

128.89 Data

Ingress LSR Labels

IP Packet

128.89.25.4 Data

Core LSR Forwards based on Label

128.89.25.4 Data

171.69
MPLS Routing: Forwarding Packets

• When the packet gets to ingress LSR where labels are assigned, there’s an IP look-up based on the IP prefix.
• It finds the forwarding table entry and it discovers that to get to the destination it should use label 4.
• It sticks that label on the front of the packet and forwards it along.
• Core LSR can just do pure label forwarding, gets in the packet with label 4, figures out that the outgoing interface is 0, and the outgoing label 9 replaces the incoming label 4.
Question

How does the MLPS domain route an IP packet with IP address 171.69.25.4?
MPLS Routing: Label Sharing

Prefixes that Share a Path Can Share Label

Remove Label One Hop Prior to De-Aggregation Point

De-Aggregation Point Does Layer-3 lookup

Prefixes that Share a Path Can Share Label

Remove Label One Hop Prior to De-Aggregation Point

De-Aggregation Point Does Layer-3 lookup
MPLS Routing: Label Sharing

• You can use the same label for all traffic heading to the same Egress LSR.
• IP packets with destination networks 128.89 and 117.59 share the same incoming and outgoing labels
• Note that the cross signs at the second router. Both labels should be stripped before forwarding to the third hop.
Question

Why is label removed one hop prior to de-aggregation point?
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• **MPLS-VPN**
Virtual Private Network (VPN)

• An IP network infrastructure delivering *private* network services over a *public* infrastructure
• Traffic from a given enterprise or group passes transparently through an internet
• Segregated from other traffic on an internet
• Performance guarantees
• Security providing
The properties of VPN

• Use a layer 3 backbone
• Scalability, easy provisioning
• Global as well as non-unique private address space
• QoS
• Controlled access
• Easy configuration for customers
MPLS-VPN Terminology

• Provider Network (P-Network)
  – The backbone under a Service Provider’s control

• PE router
  – Provider Edge router. Part of the P-Network and interfaces to Customer Edge routers

• P router
  – Provider (core) router, without knowledge of VPN
MPLS-VPN Terminology (cont.)

- **Customer Network (C-Network)**
  - Network under customer’s control

- **CE router**
  - Customer Edge router. Part of the C-network and interfaces to a PE router
MPLS VPN Connection Model

- PE routers use MPLS with P (core) routers and plain IP with CE routers
- PE and P routers share a common Interior Gateway Protocol (e.g. ISIS or OSPF)
- PE routers establish Border Gateway Protocol (BGP) sessions between them
- PE routers use BGP to exchange routing information related to the connected sites and VPNs
MPLS VPN Connection Model

BGP sessions
MPLS Packet forwarding

- PE and P routers have BGP next-hop reachability through the backbone IGP
- Labels are distributed through LDP (hop-by-hop) corresponding to BGP Next-Hops
- Label Stack is used for packet forwarding
  - Top (left most) label indicates BGP Next-Hop (interior label)
  - Second level label indicates outgoing interface (exterior label)
MPLS Packet forwarding

• MPLS nodes forward packets based on the top label
• P routers do not have BGP as well VPN knowledge
  – No VPN routing information
  – No Internet routing information (outside MPLS)
MPLS VPN Forwarding

- Ingress PE3 receives normal IP Packets from CE router of **VPN_B 10.3**
- PE3 router does “IP Longest Match” for **VPN_B 10.2**, find BGP next hop (i.e. PE2) and impose a stack of labels: Exterior Label **T2** + Interior Label **T8**

<table>
<thead>
<tr>
<th>Route Information</th>
<th>BGP next hop PE</th>
<th>T2</th>
<th>T8</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;VPN_B,10.1&gt;</td>
<td>PE1</td>
<td>T1</td>
<td>T7</td>
</tr>
<tr>
<td>&lt;VPN_B,10.2&gt;</td>
<td>PE2</td>
<td>T2</td>
<td>T8</td>
</tr>
<tr>
<td>&lt;VPN_B,10.3&gt;</td>
<td>PE3</td>
<td>T3</td>
<td>T9</td>
</tr>
<tr>
<td>&lt;VPN_A,11.6&gt;</td>
<td>PE1</td>
<td>T4</td>
<td>T7</td>
</tr>
<tr>
<td>&lt;VPN_A,10.1&gt;</td>
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<td>T5</td>
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<tr>
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<td>PE4</td>
<td>T6</td>
<td>TB</td>
</tr>
<tr>
<td>&lt;VPN_A,10.2&gt;</td>
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<td>T7</td>
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</table>
MPLS VPN Forwarding

- All Subsequent P routers do switch the packet solely on Interior Label
- Egress PE2 router removes Interior Label
- Egress PE2 uses Exterior Label to select which VPN/CE to forward the packet to
- Exterior Label is removed and packet routed to VPN_B 10.2’s CE router
Conclusions: MPLS Fundamentals

• Based on label-swapping/switching paradigm – Separate forwarding information (label) from the content of IP header

• As a packet enters an MPLS network, it is assigned a label based on its Forwarding Equivalence Class (FEC) – as determined at the edge of the MPLS network

• FECs are groups of packets forwarded over the same Label Switched Path (LSP)