MODULE 3: THE NETWORK LAYER

MODULE 3: THE NETWORK LAYER

3.1 Introduction
3.1.1 Forwarding & Routing
• The role of the network-layer is to move packets from a sending-host to a receiving-host.
• Two important functions of network-layer:
1) Forwarding
➢ Forwarding refers to transferring a packet from incoming-link to outgoing-link within a router.
➢ Forwarding is a router-local action.
2) Routing
➢ Routing means determining the path taken by packets from a sender to a receiver.
➢ Routing is a network-wide process.

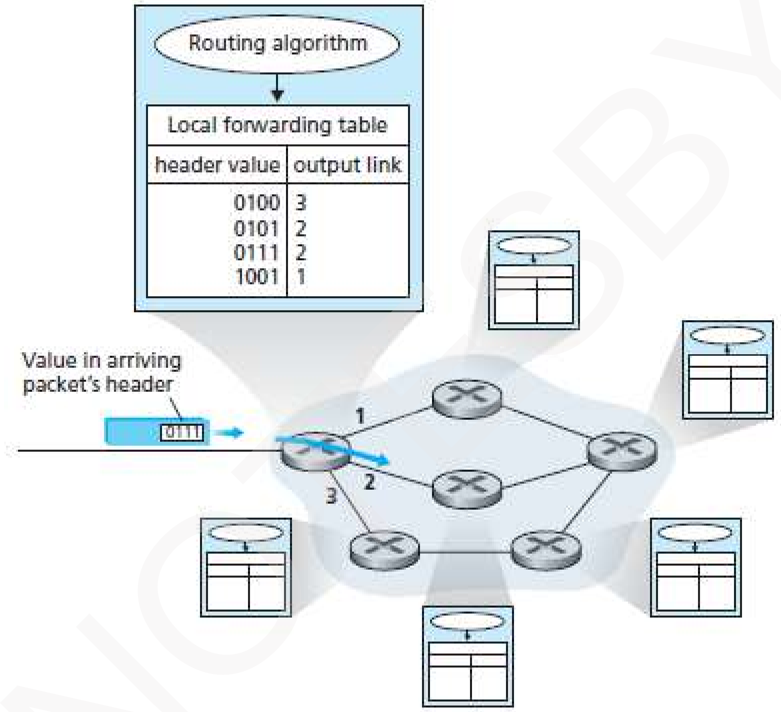


Figure 3.1: Routing-algorithms determine values in forwarding-tables

• The algorithms that determine the paths are referred to as routing-algorithms.
• Each router has a forwarding-table.
• As shown in Figure 3.1, a forwarding-table contains 2 columns:
1) Header value and
2) Output link.
• How forwarding is done?
1) Firstly, a router examines the header-value of an arriving packet.
2) Then, the router uses the header-value to index into the forwarding-table.
3) Finally, the router forwards the packet.

3.1.2 Network Service Models

- This defines the characteristics of end-to-end transport of packets b/w sending & receiving systems.
- The network-layer provides following services:

1) Guaranteed Delivery

➢ This service guarantees that the packet will eventually arrive at its destination.

2) Guaranteed Delivery with Bounded Delay

➢ This service guarantees delivery of the packet within a specified host-to-host delay bound.

3) In-order Packet Delivery

➢ This service guarantees packets arrive at the destination in the order that they were sent.

4) Guaranteed Minimal Bandwidth

➢ This service imitates the behavior of a link of a specified bit rate b/w sender & receiver.

5) Guaranteed Maximum Jitter

➢ This service guarantees

The amount of time b/w the transmissions of 2 successive packets at the sender is equal to the amount of time b/w their receipts at the destination.

6) Security Services

➢ The network-layer provides security-services such as

→ confidentiality
→ data-integrity and
→ source-authentication.

- How confidentiality is provided?

1) Using a secret key, the sender encrypts the data being sent to the receiver.
2) Then, the receiver decrypts the data using the same secret key.

3.2 Virtual Circuit & Datagram Networks

• A network-layer provides 2 types of services:
  1) Connectionless service and
  2) Connection-oriented service.

• Two categories of computer-networks:

  1) Virtual Circuit (VC) Networks
  - This provides only a connection-oriented service at the network-layer.

  2) Datagram Networks
  - This provides only a connectionless service at the network-layer.
  - For example: The Internet.

3.2.1 Virtual Circuit Networks

• A VC consists of
  1) A path between the source and destination.
  2) VC number: This is one number for each link along the path.
  3) Entries in the forwarding-table in each router.

• A packet belonging to a virtual-circuit will carry a VC number in its header.
• At intervening router, the VC number of traversing packet is replaced with a new VC number.
• The new VC number is obtained from the forwarding-table.

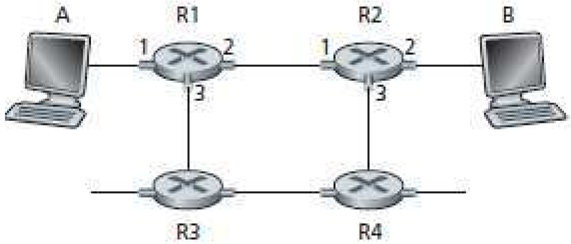


Figure 3.2: A simple virtual-circuit network

Incoming Interface	Incoming VC #	Outgoing Interface	Outgoing VC #
1	12	2	22
2	63	1	18
3	7	2	17
1	97	3	87

Table 3.1: Forwarding-table in R1

• Q: How does router determine the replacement VC number for a packet traversing the router?
Answer: Each router's forwarding-table includes VC number translation.
• The forwarding-table in R1 is shown in Table 3.1.

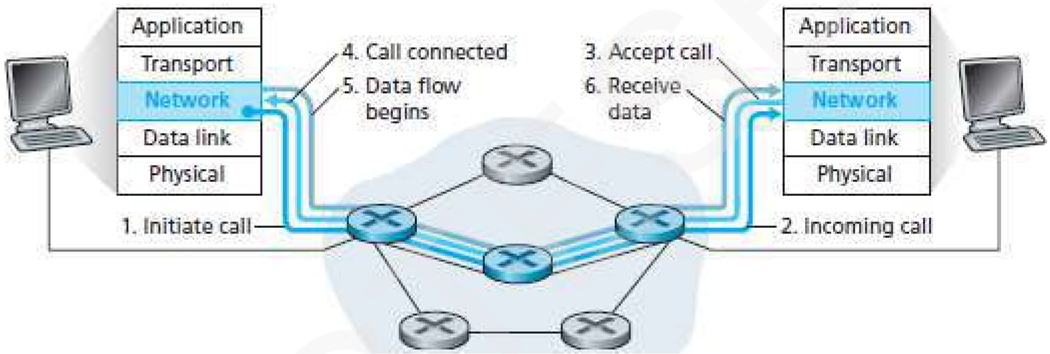


Figure 3.3: Virtual-circuit setup

• Why a packet does not use the same VC number on each link along the path?
Answer: 1) Replacing the number from link to link reduces length of the VC field in the packet-header.
2) VC setup is simplified by permitting a different VC number at each link along the path.
• Disadvantage:
The routers must maintain connection state information for the ongoing connections.
• Three phases in a virtual-circuit (Figure 3.3):

1) VC Setup
➢ During the setup phase, the sending transport-layer
→ contacts the network-layer
→ specifies the receiver's address and
→ waits for the network to set-up the VC.
➢ The network-layer determines the path between sender and receiver.
➢ The network-layer also determines the VC number for each link along the path.
➢ Finally, the network-layer adds an entry in the forwarding-table in each router.
➢ During VC setup, the network-layer may also reserve resources.

2) Data Transfer
➢ Once the VC has been established, packets can begin to flow along the VC.

3) VC Teardown
➢ This is initiated when the sender/receiver wants to terminate the VC.
➢ The network-layer
→ informs the other end-system of the call termination and
→ removes the appropriate entries in the forwarding-table in each router.

3.2.2 Datagram Networks

- The source attaches the packet with the address of the destination.
- The packets are injected into the network.
- The packets are routed independent of each other.
- No advance circuit setup is needed. So, routers do not maintain any connection state information.
- As a packet is transmitted from source to destination, it passes through a series of routers.
- Each router uses the packet's destination-address to forward the packet.

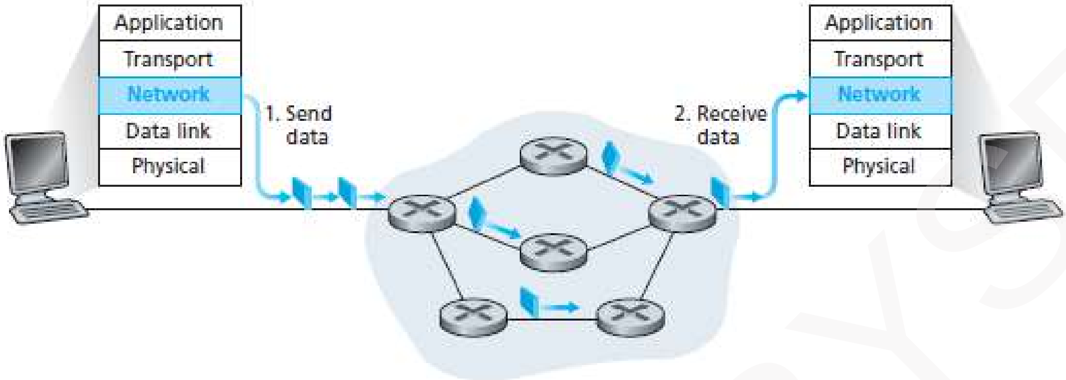


Figure 3.4: Datagram network

- Suppose the router R1 has four links, numbered 0 through 3 (Figure 3.4).
- Forwarding-table of R1 is as follows (Table 3.2):

Prefix Match	Link Interface
11001000 00010111 00010	0
11001000 00010111 00011000	1
11001000 00010111 00011	2
otherwise	3

Table 3.2: Forwarding-table of R1

- The router matches a prefix of the packet's destination-address with the entries in the table;
  1) If both are equal, the router forwards the packet to an associated link. (0, 1 or 2)
  2) If both are unequal, the router forwards the packet to a default link (otherwise 3).
- When there are multiple matches, the router uses the longest prefix matching rule.

3.2.3 Comparison of Virtual Circuit & Datagram

Issue	Datagram	Virtual Circuit
Connection Setup	None	Required
Addressing	Packet contains full source and destination-address	Packet contains short virtual-circuit number identifier
State Information	None other than router table containing destination-network	Each virtual-circuit number entered to table on setup, used for routing
Routing	Packets routed independently	Route established at setup, all packets follow same route
Effect of Router Failure	Only on packets lost during crash	All virtual circuits passing through failed router terminated

3.3 What's Inside a Router?

• The router is used for transferring packets from an incoming-links to the appropriate outgoing-links.

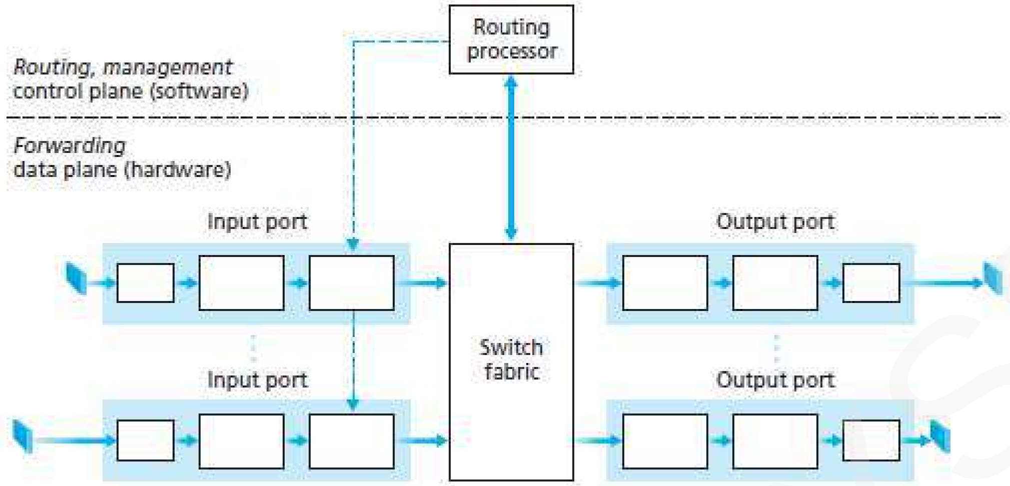


Figure 3.5: Router architecture

• Four components of router (Figure 3.5):

1) Input Ports

• An input-port is used for terminating an incoming physical link at a router (Figure 3.6).
• It is used for interoperating with the link layer at the other side of the incoming-link.
• It is used for lookup function i.e. searching through forwarding-table looking for longest prefix match.
• It contains forwarding-table.
• Forwarding-table is consulted to determine output-port to which arriving packet will be forwarded.
• Control packets are forwarded from an input-port to the routing-processor.
• Many other actions must be taken:
   i) Packet's version number, checksum and time-to-live field must be checked.
   ii) Counters used for network management must be updated.

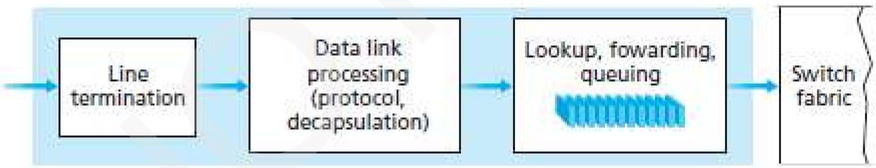


Figure 3.6: Input port processing

2) Switching Fabric

• The switching fabric connects the router's input-ports to its output-ports.
• In fabric, the packets are switched (or forwarded) from an input-port to an output-port.
• In fact, fabric is a network inside of a router.
• A packet may be temporarily blocked if packets from other input-ports are currently using the fabric.
• A blocked packet will be queued at the input-port & then scheduled to send at a later point in time.

3) Output Ports

• An output-port
   → stores packets received from the switching fabric and
   → transmits the packets on the outgoing-link.
• For a bidirectional link, an output-port will typically be paired with the input-port.

4) Routing Processor

• The routing-processor
   → executes the routing protocols
   → maintains routing-tables & attached link state information and
   → computes the forwarding-table.
• It also performs the network management functions.

3.3.1 Switching

• Three types of switching fabrics (Figure 3.7):
  1) Switching via memory
  2) Switching via a bus and
  3) Switching via an interconnection network.

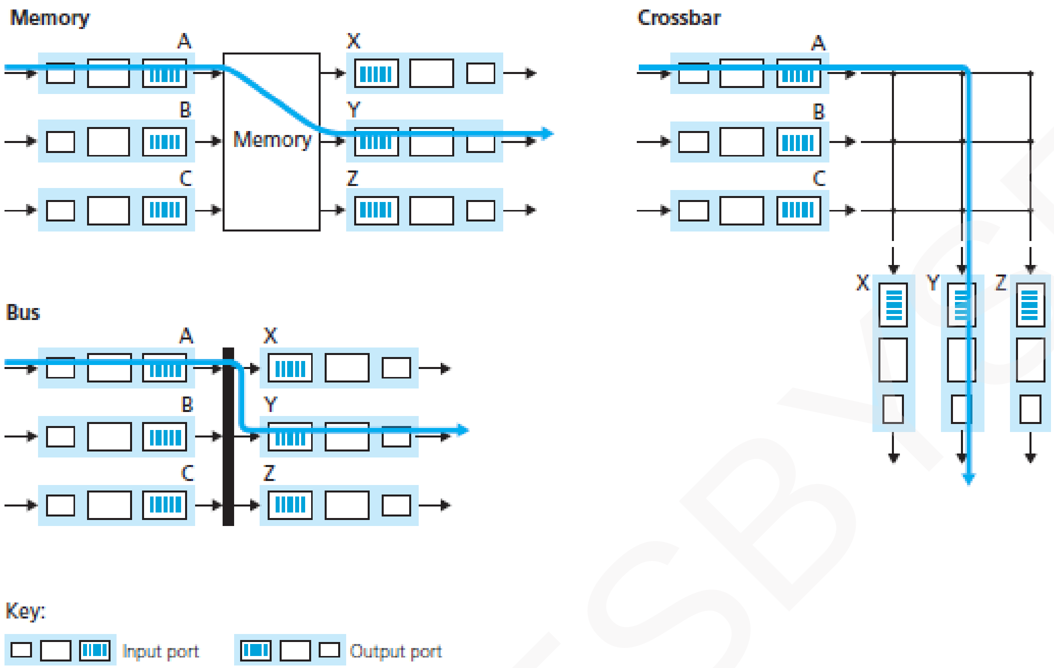


Figure 3.7: Three switching techniques

3.3.1.1 Switching via Memory

• Switching b/w input-ports & output-ports is done under direct control of CPU i.e. routing-processor.
• Input and output-ports work like a traditional I/O devices in a computer.
• Here is how it works (Figure 3.7a):
  i) On arrival of a packet, the input-port notifies the routing-processor via an interrupt.
  ii) Then, the packet is copied from the input-port to processor-memory.
  iii) Finally, the routing-processor
    → extracts the destination-address from the header
    → looks up the appropriate output-port in the forwarding-table and
    → copies the packet into the output-port's buffers.
• Let memory-bandwidth = B packets per second.
  Thus, the overall forwarding throughput must be less than B/2.
• Disadvantage:
  ➢ Multiple packets cannot be forwarded at the same time. This is because
    → only one memory read/write over the shared system bus can be done at a time.

3.3.1.2 Switching via a Bus

• Switching b/w input-ports & output-ports is done without intervention by the routing-processor.
• Here is how it works (Figure 3.7b):
  i) The input-port appends a switch-internal label (header) to the packet.
  ➢ The label indicates the local output-port to which the packet must be transferred.
  ii) Then, the packet is received by all output-ports.
  ➢ But, only the port that matches the label will keep the packet.
  iii) Finally, the label is removed at the output-port.
• Disadvantages:
  i) Multiple packets cannot be forwarded at the same time. This is because
    → only one packet can cross the bus at a time.
  ii) The switching speed of the router is limited to the bus-speed.

3.3.1.3 Switching via an Interconnection Network

- A crossbar switch is an interconnection network.
- The network consists of 2N buses that connect N input-ports to N output-ports.
- Each vertical bus intersects each horizontal bus at a crosspoint.
- The crosspoint can be opened or closed at any time by the switch-controller.
- Here is how it works (Figure 3.7c):
    1) To move a packet from port A to port Y, the switch-controller closes the crosspoint at the intersection of buses A and Y.
    2) Then, port A sends the packet onto its bus, which is picked up by bus Y.
- Advantage:
    - ➢ Crossbar networks are capable of forwarding multiple packets in parallel.
    - ➢ For ex: A packet from port B can be forwarded to port X at the same time. This is because
        → A-to-Y and B-to-X packets use different input and output buses.
- Disadvantage:
    - ➢ If 2 packets have to use same output-port, then one packet has to wait. This is because
        → only one packet can be sent over any given bus at a time.

3.3.2 Output Processing

- Output-port processing
    → takes the packets stored in the output-port's memory and
    → transmits the packets over the output link (Figure 3.8).
- This includes
    → selecting and dequeueing packets for transmission and
    → performing the linklayer and physical-layer transmission functions.

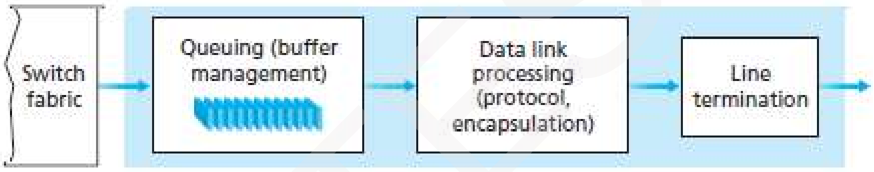


Figure 3.8: Output port processing

3.3.3 Where Does Queueing Occur?

- Packet queues may form at both the input-ports & the output-ports (Figure 3.9).
- As the queues grow large, the router's memory can be exhausted and packet loss will occur.
- The location and extent of queueing will depend on
  1) The traffic load
  2) The relative speed of the switching fabric and
  3) The line speed
- Switching fabric transfer rate R_{switch} is defined as
  "The rate at which packets can be moved from input-port to output-port".
- If R_{switch} is N times faster than R_{line}, then only negligible queuing will occur at the input-ports.

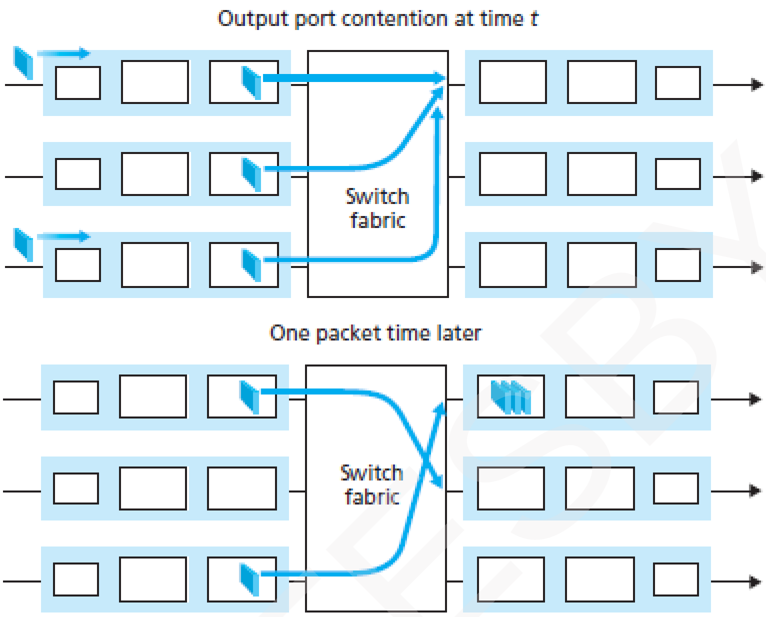


Figure 3.9: Output port queuing

- At output-port, packet-scheduler is used to choose one packet among those queued for transmission.
- The packet-scheduling can be done using
  → first-come-first-served (FCFS) or
  → weighted fair queuing (WFQ).
- Packet scheduling plays a crucial role in providing QoS guarantees.
- If there is less memory to hold an incoming-packet, a decision must be made to either
  1) Drop the arriving packet (a policy known as drop-tail) or
  2) Remove one or more already-queued packets to make room for the newly arrived packet.

3.4 IP: Forwarding & Addressing in the Internet

• IP(Internet Protocol) is main protocol responsible for packetizing, forwarding & delivery of a packet at network-layer.
• It is a connection-less & unreliable protocol.
    i) Connection-less means there is no connection setup b/w the sender and the receiver.
    ii) Unreliable protocol means
        → IP does not make any guarantee about delivery of the data.
        → Packets may get dropped during transmission.
• It provides a best-effort delivery service.
• Best effort means IP does its best to get the packet to its destination, but with no guarantees.
• If reliability is important, IP must be paired with a TCP which is reliable transport-layer protocol.
• IP does not provide following services
    → flow control
    → error control
    → congestion control services.

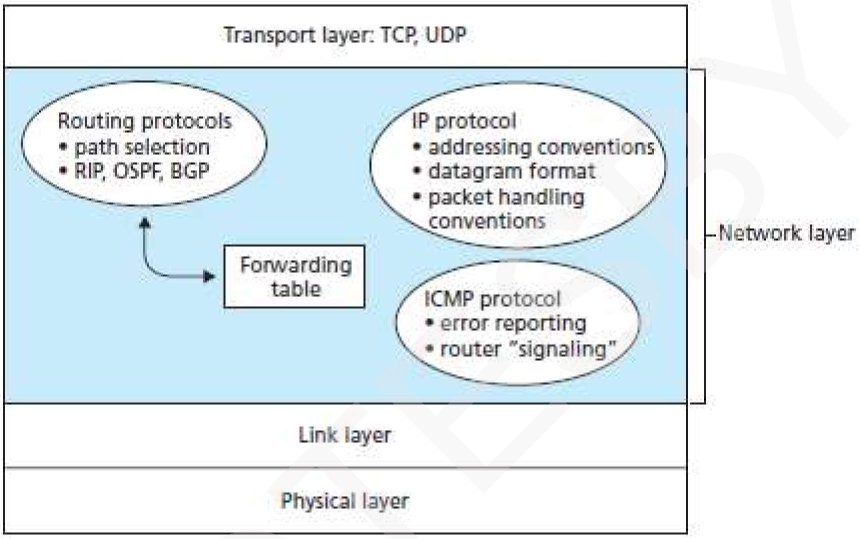


Figure 3.10: A look inside the Internet's network-layer

• Two important components of IP:
    1) Internet addressing and
    2) Forwarding
• There are two versions of IP in use today.
    1) IP version 4 (IPv4) and
    2) IP version 6 (IPv6)
• As shown in Figure 3.10, the network-layer has three major components:
    1) IP protocol
    2) Routing component determines the path a data follows from source to destination
    3) Network-layer is a facility to report errors in datagrams

3.4.1 IPv4 Datagram Format

• IP uses the packets called datagrams.
• A datagram consist of 2 parts: 1) Payload (or Data) 2) Header.

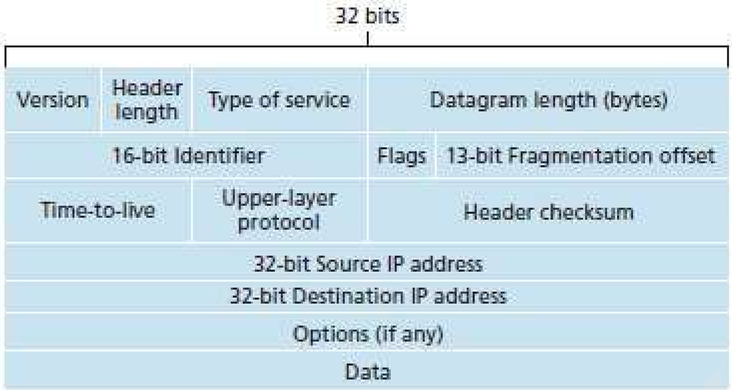


Figure 3.11: IPv4 datagram format

1) Payload (or Data)
• This field contains the data to be delivered to the destination.
2) Header
• Header contains information essential to routing and delivery.
• IP header contains following fields (Figure 3.11):

1) Version
➢ This field specifies version of the IPv4 datagram, i.e. 4.

2) Header Length
➢ This field specifies length of header.
➢ Without options field, header-length = 5 bytes.

3) Type of Service (TOS)
➢ This field specifies priority of packet based on parameters such as delay, throughput, reliability & cost.

4) Datagram Length
➢ This field specifies the total length of the datagram (header + data).
➢ Maximum length = 65535 bytes.

5) Identifier, Flags, Fragmentation Offset
➢ These fields are used for fragmentation and reassembly.
➢ Fragmentation occurs when the size of the datagram is larger than the MTU of the network.
i) Identifier: This field uniquely identifies a datagram packet.
ii) Flags: It is a 3-bit field. The first bit is not used.
The second bit D is called the do not fragment bit.
The third bit M is called the more fragment bit.
iii) Fragmentation Offset: This field identifies location of a fragment in a datagram.

6) Time-To-Live (TTL)
➢ This defines lifetime of the datagram (default value 64) in hops.
➢ Each router decrements TTL by 1 before forwarding. If TTL is zero, the datagram is discarded.

7) Protocol
➢ This field specifies upper-layer protocol used to receive the datagram at the destination-host.
➢ For example, TCP=6 and UDP=17.

8) Header Checksum
➢ This field is used to verify integrity of header only.
➢ If the verification process fails, the packet is discarded.

9) Source IP Address & Destination IP Address
➢ These fields contain the addresses of source and destination respectively.

10) Options
➢ This field allows the packet to request special features such as
→ security level
→ route to be taken by packet at each router.

3.4.2 Fragmentation
3.4.2.1 Maximum Transfer Unit
• Each network imposes a restriction on maximum size of packet that can be carried. This is called the MTU (maximum transmission unit).
• For example:
MTU Ethernet = 1500 bytes
MTU FDDI = 4464 bytes
• Fragmentation means
"The datagram is divided into smaller fragments when size of a datagram is larger than MTU"
• Each fragment is routed independently (Figure 3.12).
• A fragmented datagram may be further fragmented, if it encounters a network with a smaller MTU.
• Source/router is responsible for fragmentation of original datagram into the fragments.
Only destination is responsible for reassembling the fragments into the original datagram.

3.4.2.2 Fields Related to Fragmentation & Reassembly
• Three fields in the IP header are used to manage fragmentation and reassembly:
1) Identification 2) Flags 3) Fragmentation offset.

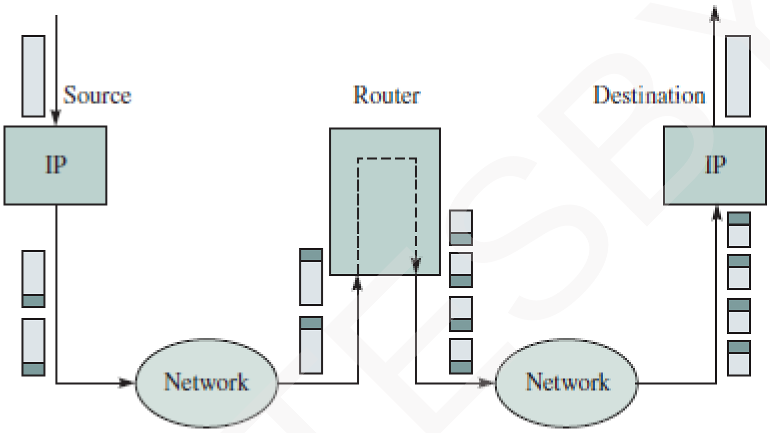


Figure 3.12: IP fragmentation and reassembly

1) Identification
• This field is used to identify to which datagram a particular fragment belongs to (so that fragments for different packets do not get mixed up).
• When a datagram is created, the source attaches the datagram with an identification-number.
• When a datagram is fragmented, the value in the identification-field is copied into all fragments.
• The identification-number helps the destination in reassembling the datagram.

2) Flags
• This field has 3 bits.
i) The first bit is not used.
ii) DF bit (Don't Fragment):
a) If DF=1, the router should not fragment the datagram. Then, the router discards the datagram.
b) If DF=0, the router can fragment the datagram.
iii) MF bit (More Fragment):
a) If MF=1, there are some more fragments to come.
b) If MF=0, this is last fragment.

3) Fragmentation Offset
• This field identifies location of a fragment in a datagram.
• This field is the offset of the data in the original datagram.

3.4.3 IPv4 Addressing

- IP address is a numeric identifier assigned to each machine on the internet.
- IP address consists of two parts: network ID(NID) and host ID(HID).
  1) NID identifies the network to which the host is connected. All the hosts connected to the same network have the same NID.
  2) HID is used to uniquely identify a host on that network.
- HID is assigned by the network-administrator at the local site.
  NID for an organization may be assigned by the ISP (Internet Service Provider).
- IPv4 uses 32-bit addresses, i.e., approximately 4 billion addresses (2^{32}).
- IP addresses are usually written in dotted-decimal notation. The address is broken into four bytes.
  For example, an IP address of
  10000000 10000111 01000100 00000101
  is written as
  128.135.68.5
- IP address can be classified as
  1) Classful IP addressing &
  2) Classless IP addressing (CIDR → Classless Inter Domain Routing)

3.4.3.1 IPv4 Classful Addressing

- In classful addressing, the address space is divided into five classes: A, B, C, D and E.
- IP address class is identified by MSBs in binary.
- Classes A, B and C are used for unicast addressing. (Figure 3.13).
- Class D was designed for multicasting and class E is reserved.

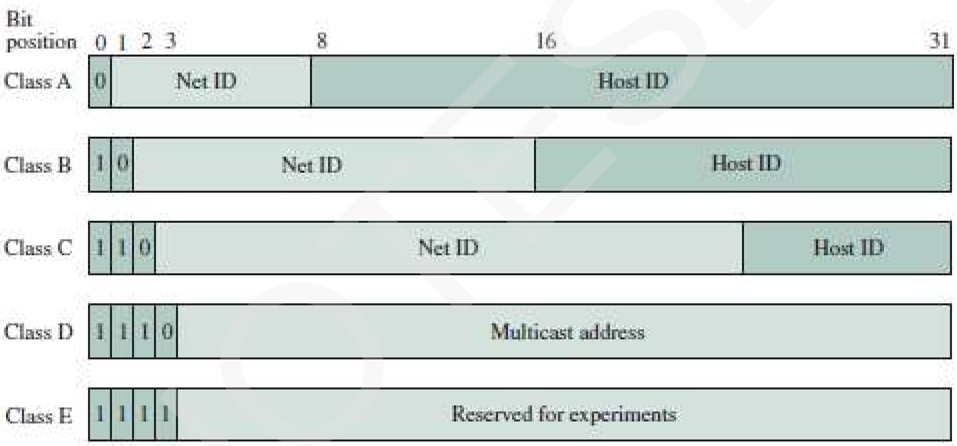


Figure 3.13: The five classes of IP addresses

Class	No. of networks	Max. No. of hosts per network	Designed for
A	126	$2^{24} - 2$	WAN
B	16,382	65,534	Campus networks
C	2^{21}	254	LAN

Table 3.3: Classful Addressing

- Analysis:
  - ➢ In c1assful addressing, a large part of the available addresses were wasted, since Class A and B were too large for most organizations (Table 3.3).
  - ➢ Class C is suited only for small organization and reserved addresses were sparingly used.

3.4.3.1.1 Subnet Addressing

• Problem with classful addressing:
  ➢ Consider an organization has a Class B address which can support about 64,000 hosts.
  ➢ It will be a huge task for the network-administrator to manage all 64,000 hosts.

• Solution: Use subnet addressing.

• Subnetting reduces the total number of network-numbers by assigning a single network-number to many adjacent physical networks.

• Each adjacent physical network is referred to as subnet. (Figure 3.14).

• All nodes on a subnet are configured with a subnet mask. For example: 255.255.255.0.

• The 1's in the subnet-mask represent the positions that refer to the network or subnet-numbers. The 0's represent the positions that refer to the host part of the address.

• The bitwise AND of IP address and its subnet mask gives the subnet number.

• Advantage:
  ➢ The subnet-addressing scheme is oblivious to the network outside the organization.
  ➢ Inside the organization the network-administrator is free to choose any combination of lengths for the subnet & host ID fields.

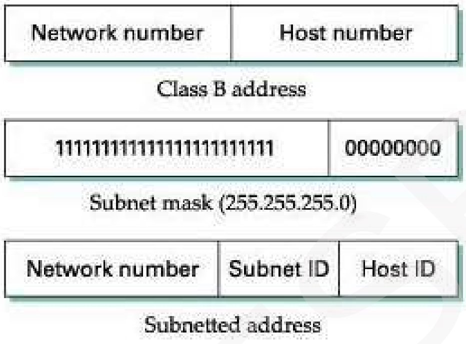


Figure 3.14: Subnet addressing

Question: If a packet with a destination IP address of 150.100.12.176 arrives at site from the outside network, which subnet should a router forward this packet to? Assume subnet mask is 255.255.255.128 (Figure 3.15).

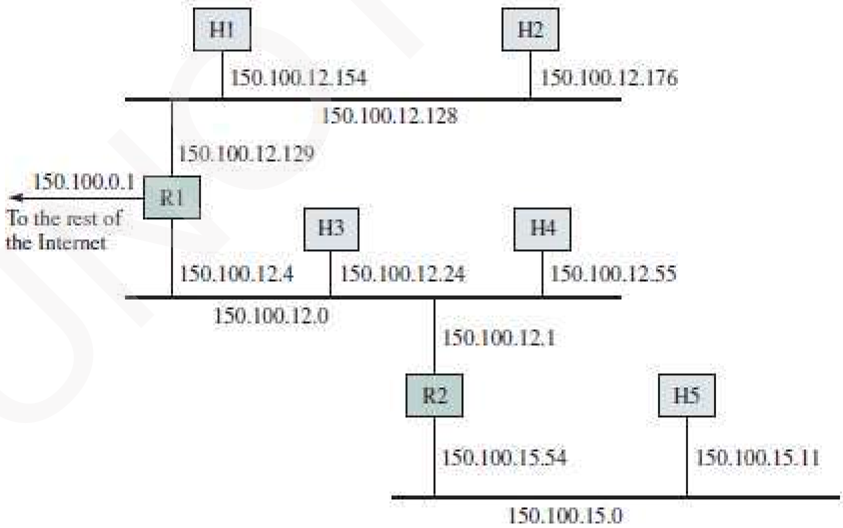


Figure 3.15: Example of address assignment with subnetting

Solution: The router can determine the subnet number by performing a binary AND between the subnet mask and the IP address.

IP address:	10010110	01100100	00001100	10110000(150.100.12.176)
Subnet mask:	11111111	11111111	11111111	10000000(255.255.255.128)
Subnet number:	10010110	01100100	00001100	10000000(150.100.12.128)

This number (150.100.12.128) is used to forward the packet to the correct subnet work inside the organization.

3.4.3.2 CIDR

• Problem with classful IP addressing:

  ➢ Consider an organization needs about 500 hosts.
  ➢ Obviously, the organization will get a Class B license, even though it has far fewer than 64,000 hosts.
  ➢ At most, over 64,000 addresses can go unused.
  ➢ This results in inefficient usage of the available address-space.

• Solution: Use CIDR (Classless Inter Domain Routing).

  ➢ A single IP address can be used to designate many unique IP addresses. This is called supernetting.
  ➢ A CIDR IP address looks like a normal IP address except that
    → the address ends with a slash followed by a number, called the IP network prefix.
      For ex: 205.100.0.0/22
  ➢ CIDR addresses
    → reduce the size of routing-tables and
    → make more IP addresses available within organizations.

3.4.3.3 Obtaining a Block of Addresses

• To obtain a block of IP addresses for use within an organization's subnet, a network-administrator contacts the ISP.

• IP addresses are managed under the authority of the ICANN.

• The responsibility of the ICANN (Internet Corporation for Assigned Names and Numbers):

  → to allocate IP addresses,
  → to manage the DNS root servers.
  → to assign domain names and resolve domain name disputes.
  → to allocate addresses to regional Internet registries.

3.4.3.4 Obtaining a Host Address: DHCP

• Two ways to assign an IP address to a host:

  1) Manual Configuration
  ➢ Operating systems allow system-administrator to manually configure IP address.
  2) Dynamic Host Configuration Protocol (DHCP)
  ➢ DHCP enables auto-configuration of IP address to host.

3.4.3.4.1 DHCP Protocol

- DHCP enables auto-configuration of IP address to host.
- DHCP assigns dynamic IP addresses to devices on a network.
- Dynamic address allocation is required
  - → when a host moves from one network to another or
  - → when a host is connected to a network for the first time.

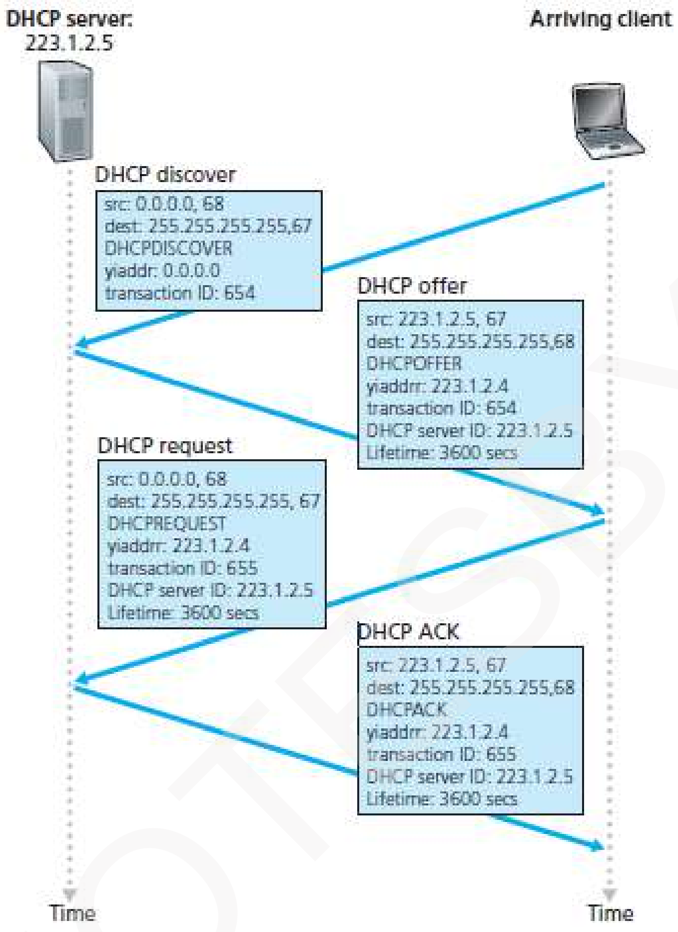


Figure 3.16: DHCP client-server interaction

- Four steps in DHCP protocol (Figure 3.16):

1) DHCP Server Discovery

➢ DHCP server contains a range of unassigned addresses to be assigned to hosts on-demand.

➢ To contact DHCP server, a client broadcasts a DHCPDISCOVER message with destination IP address 255.255.255.255.

2) DHCP Server Offer

➢ DHCP server broadcasts DHCPOFFER message containing
  - → client's IP address
  - → network mask and
  - → IP address lease time (i.e. the amount of time for which the IP address will be valid).

3) DHCP Request

➢ The client sends a DHCPREQUEST message, requesting the offered address.

4) DHCP ACK

➢ The DHCP server acknowledges with a DHCPACK message containing the requested configuration.

3.4.3.5 NAT

• Network Address Translation (NAT) enables hosts to use Internet without the need to have globally unique addresses.
• NAT enables organization to have a large set of addresses internally and one address externally.
• The organization must have single connection to the Internet through a NAT-enabled router.
• NAT allows a single device (such as a router) to act as an agent b/w
    1) Internet (or "public network") and
    2) Local (or "private") network.
• This means only a single, unique IP address is required to represent an entire group of computers.
• Figure 3.17 shows the operation of a NAT-enabled router.

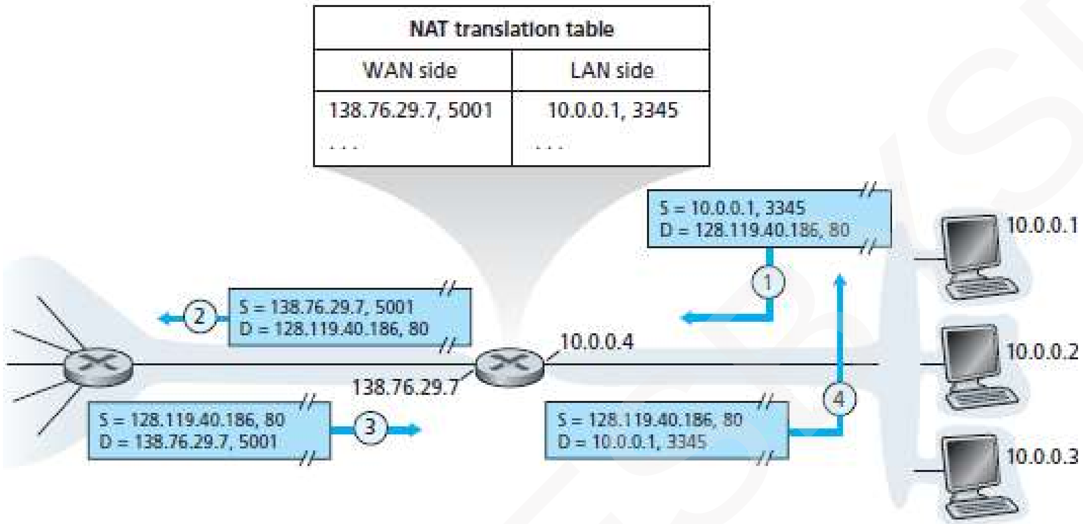


Figure 3.17: Network address translation

• The private addresses only have meaning to devices within a given network.
• The NAT-enabled router does not look like a router to the outside world.
• Instead, the NAT-enabled router behaves to the outside world as a single device with a single IP address.
• In Figure 3.17,
    1) All traffic leaving the home-router for the Internet has a source-address of 138.76.29.7.
    2) All traffic entering the home-router must have a destination-address of 138.76.29.7.
• The NAT-enabled router is hiding the details of the home-network from the outside world.
• At the NAT router, NAT translation-table includes
    1) Port numbers and
    2) IP addresses.
• IETF community is against the use of NAT. This is because of following reasons:
    1) They argue, port numbers are to be used for addressing processes, not for addressing hosts.
    2) They argue routers are supposed to process packets only up to layer 3.
    3) They argue the NAT protocol violates the end-to-end argument.
    4) They argue, we should use IPv6 to solve the shortage of IP addresses.
    5) NAT interferes with P2P applications. If Peer B is behind NAT, Peer B cannot act as a server.

3.4.4 ICMP
• ICMP is a network-layer protocol. (ICMP → Internet Control Message Protocol).
• This is used to handle error and other control messages.
• Main responsibility of ICMP: To report errors that occurs during the processing of the datagram.
• ICMP does not correct errors; ICMP simply reports the errors to the source.
• 12 types of ICMP messages are defined as shown in Table 3.4.
• Each ICMP message type is encapsulated in an IP packet.

ICMP Type	Code	Description
0	0	echo reply (to ping)
3	0	destination network unreachable
3	1	destination host unreachable
3	2	destination protocol unreachable
3	3	destination port unreachable
3	6	destination network unknown
3	7	destination host unknown
4	0	source quench (congestion control)
8	0	echo request
9	0	router advertisement
10	0	router discovery
11	0	TTL expired
12	0	IP header bad

Table 3.4: ICMP message types

1) Destination Unreachable (Type=3)
• This message is related to problem reaching the destinations.
• This message uses different codes (0 to 15) to define type of error-message.
• Possible values for code field:

Code 0 = network unreachable   Code 1 = host unreachable
Code 2 = protocol unreachable   Code 3 = port unreachable

2) Source Quench (Type=4)
• The main purpose is to perform congestion control.
• This message
→ informs the sender that network has encountered congestion & datagram has been dropped.
→ informs the sender to reduce its transmission-rate.

3) Echo Request & Echo Reply (Type=8 & Type=0)
• These messages are used to determine whether a remote-host is alive.
• A source sends an echo request-message to destination;
If the destination is alive, the destination responds with an echo reply message.
• Type=8 is used for echo request;
Type=0 is used for echo reply.
• These messages can be used in two debugging tools: ping and traceroute.

i) Ping
➢ The ping program can be used to find if a host is alive and responding.
➢ The source-host sends ICMP echo-request-messages.
➢ The destination, if alive, responds with ICMP echo-reply messages.

ii) Traceroute
➢ The traceroute program can be used to trace the path of a packet from source to destination.
➢ It can find the IP addresses of all the routers that are visited along the path.
➢ The program is usually set to check for the maximum of 30 hops (routers) to be visited.

3.4.5 IPv6

• CIDR, subnetting and NAT could not solve address-space exhaustion faced by IPv4.
• IPv6 was evolved to solve this problem.

3.4.5.1 Changes from IPv4 to IPv6 (Advantages of IPv6)

1) Expanded Addressing Capabilities

- IPv6 increases the size of the IP address from 32 to 128 bits (Supports upto 3.4×10^{38} nodes).
- In addition to unicast & multicast addresses, IPv6 has an anycast address.
- Anycast address allows a datagram to be delivered to only one member of the group.

2) A Streamlined 40-byte Header

- A number of IPv4 fields have been dropped or made optional.
- The resulting 40-byte fixed-length header allows for faster processing of the IP datagram.
- A new encoding of options field allows for more flexible options processing.

3) Flow Labeling & Priority

- A flow can be defined as
  "Labeling of packets belonging to particular flows for which the sender requests special handling".
- For example:
  Audio and video transmission may be treated as a flow.

3.4.5.2 IPv6 Datagram Format

• The format of the IPv6 datagram is shown in Figure 3.18.

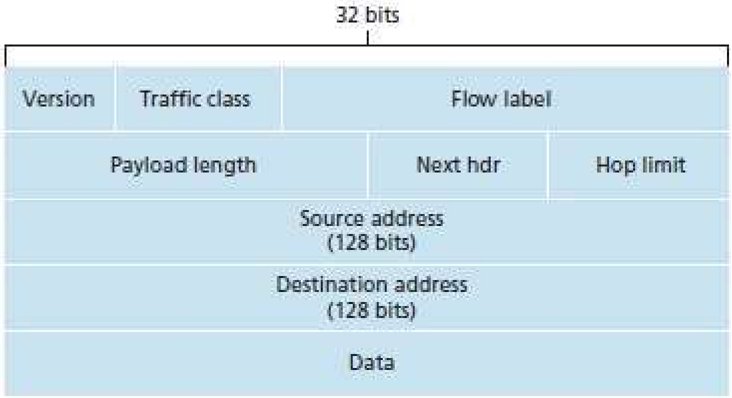


Figure 3.18: IPv6 datagram format

• The following fields are defined in IPv6:

1) Version

➢ This field specifies the IP version, i.e., 6.

2) Traffic Class

➢ This field is similar to the TOS field in IPv4.
➢ This field indicates the priority of the packet.

3) Flow Label

➢ This field is used to provide special handling for a particular flow of data.

4) Payload Length

➢ This field shows the length of the IPv6 payload.

5) Next Header

➢ This field is similar to the options field in IPv4 (Figure 3.19).
➢ This field identifies type of extension header that follows the basic header.

6) Hop Limit

➢ This field is similar to TTL field in IPv4.
➢ This field shows the maximum number of routers the packet can travel.
➢ The contents of this field are decremented by 1 by each router that forwards the datagram.
➢ If the hop limit count reaches 0, the datagram is discarded.

7) Source & Destination Addresses

➢ These fields show the addresses of the source & destination of the packet.

8) Data

➢ This field is the payload portion of the datagram.
➢ When the datagram reaches the destination, the payload will be
→ removed from the IP datagram and
→ passed on to the upper layer protocol (TCP or UDP).

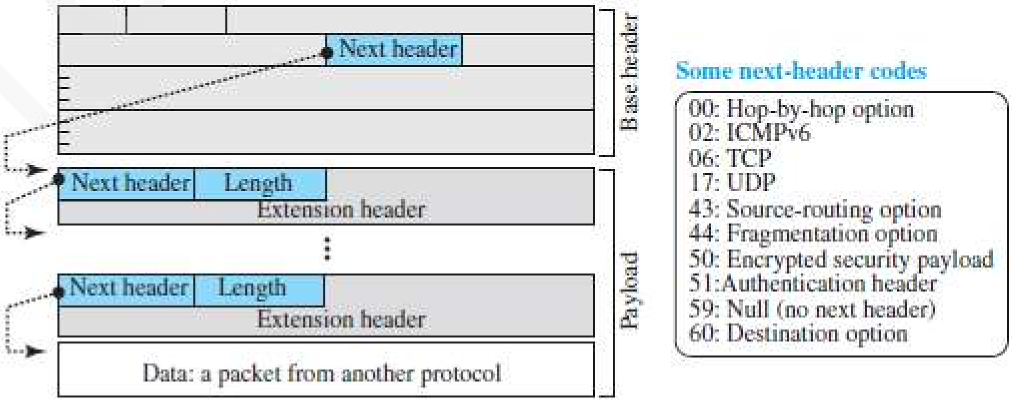


Figure 3.19: Payload in IPv6 datagram

3.4.5.3 IPv4 Fields not present in IPv6

1) Fragmentation/Reassembly

- Fragmentation of the packet is done only by the source, but not by the routers.
  The reassembling is done by the destination.
- Fragmentation & reassembly is a time-consuming operation.
- At routers, the fragmentation is not allowed to speed up the processing in the router.
- If packet-size is greater than the MTU of the network, the router
  → drops the packet.
  → sends an error message to inform the source.

2) Header Checksum

- In the Internet layers, the transport-layer and link-layer protocols perform check summing.
- This functionality was redundant in the network-layer.
- So, this functionality was removed to speed up the processing in the router.

3) Options

- In, IPv6, next-header field is similar to the options field in IPv4.
- This field identifies type of extension header that follows the basic header.
- To support extra functionalities, extension headers can be placed b/w base header and payload.

3.4.5.4 Difference between IPv4 & IPv6

	IPv4	IPv6
1	IPv4 addresses are 32 bit length	IPv6 addresses are 128 bit length
2	Fragmentation is done by sender and forwarding routers	Fragmentation is done only by sender
3	Does not identify packet flow for QoS handling	Contains Flow Label field that specifies packet flow for QoS handling
4	Includes Options up to 40 bytes	Extension headers used for optional data
5	Includes a checksum	Does not includes a checksum
6	Address Resolution Protocol (ARP) is available to map IPv4 addresses to MAC addresses	Address Resolution Protocol (ARP) is replaced with Neighbor Discovery Protocol (NDP)
7	Broadcast messages are available	Broadcast messages are not available
8	Manual configuration (Static) of IP addresses or DHCP (Dynamic configuration) is required to configure IP addresses	Auto-configuration of addresses is available
9	IPSec is optional, external	IPSec is required

3.4.5.5 Transitioning from IPv4 to IPv6
• IPv4-capable systems are not capable of handling IPv6 datagrams.
• Two strategies have been devised for transition from IPv4 to IPv6:
1) Dual stack and
2) Tunneling.

3.4.5.5.1 Dual Stack Approach
• IPv6-capable nodes also have a complete IPv4 implementation. Such nodes are referred to as IPv6/IPv4 nodes.
• IPv6/IPv4 node has the ability to send and receive both IPv4 and IPv6 datagrams.
• When interoperating with an IPv4 node, an IPv6/IPv4 node can use IPv4 datagrams.
When interoperating with an IPv6 node, an IPv6/IPv4 node can use IPv6 datagrams.
• IPv6/IPv4 nodes must have both IPv6 and IPv4 addresses.
• IPv6/IPv4 nodes must be able to determine whether another node is IPv6-capable or IPv4-only.
• This problem can be solved using the DNS.
If the node name is resolved to IPv6-capable, then the DNS returns an IPv6 address
Otherwise, the DNS return an IPv4 address.
• If either the sender or the receiver is only IPv4-capable, an IPv4 datagram must be used.
• Two IPv6-capable nodes can send IPv4 datagrams to each other.

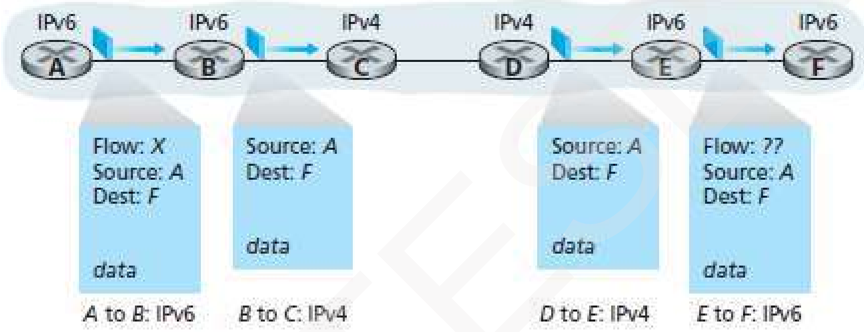


Figure 3.20: A dual-stack approach

• Dual stack is illustrated in Figure 3.20.
• Here is how it works:
1) Suppose IPv6-capable Node-A wants to send a datagram to IPv6-capable Node-F.
2) IPv6-capable Node-B creates an IPv4 datagram to send to IPv4-capable Node-C.
3) At IPv6-capable Node-B, the IPv6 datagram is copied into the data field of the IPv4 datagram and appropriate address mapping can be done.
4) At IPv6-capable Node-E, the IPv6 datagram is extracted from the data field of the IPv4 datagram.
5) Finally, IPv6-capable Node-E forwards an IPv6 datagram to IPv6-capable Node-F.
• Disadvantage: During transition from IPv6 to IPv4, few IPv6-specific fields will be lost.

3.4.5.5.2 Tunneling

• Tunneling is illustrated in Figure 3.21.
• Suppose two IPv6-nodes B and E
  → want to interoperate using IPv6 datagrams and
  → are connected by intervening IPv4 routers.
• The intervening-set of IPv4 routers between two IPv6 routers are referred as a tunnel.
• Here is how it works:
  ➢ On the sending side of the tunnel:
    → IPv6-node B takes & puts the IPv6 datagram in the data field of an IPv4 datagram.
    → The IPv4 datagram is addressed to the IPv6-node E.
  ➢ On the receiving side of the tunnel: The IPv6-node E
    → receives the IPv4 datagram
    → extracts the IPv6 datagram from the data field of the IPv4 datagram and
    → routes the IPv6 datagram to IPv6-node F

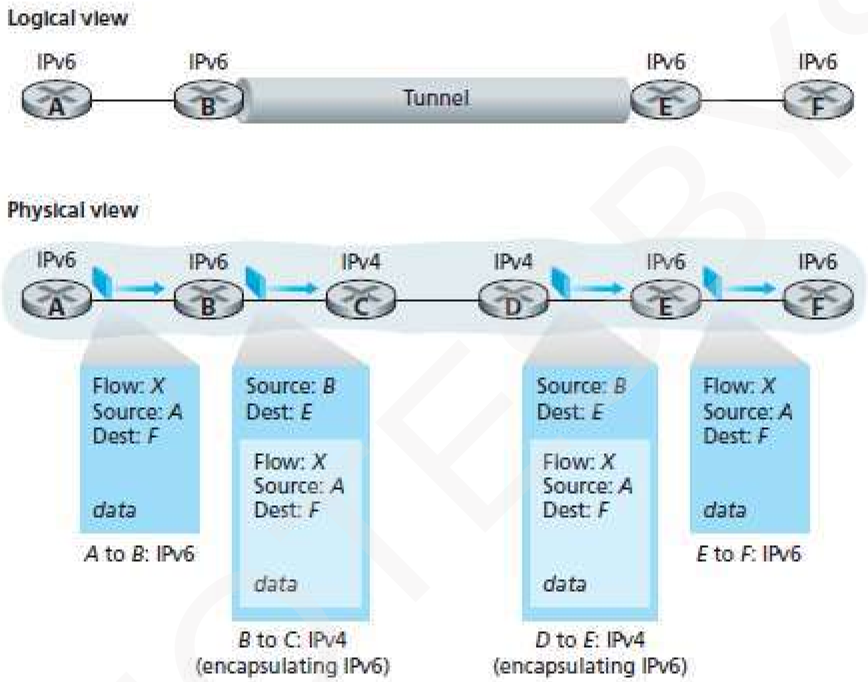


Figure 3.21: Tunneling

3.4.6 A Brief Foray into IP Security

- IPsec is a popular secure network-layer protocol.
- It is widely deployed in Virtual Private Networks (VPNs).
- It has been designed to be backward compatible with IPv4 and IPv6.
- It can be used to create a connection-oriented service between 2 entities.
- In transport mode, 2 hosts first establish an IPsec session between themselves.
- All TCP and UDP segments sent between the two hosts enjoy the security services provided by IPsec.
- On the source-side,
  1) The transport-layer passes a segment to IPsec.
  2) Then, IPsec
     → encrypts the segment
     → appends additional security fields to the segment and
     → encapsulates the resulting payload in a IP datagram.
  3) Finally, the sending-host sends the datagram into the Internet.
  ➢ The Internet then transports the datagram to the destination-host.
- On the destination-side,
  1) The destination receives the datagram from the Internet.
  2) Then, IPsec
     → decrypts the segment and
     → passes the unencrypted segment to the transport-layer.
- Three services provided by an IPsec:
  1) Cryptographic Agreement
  ➢ This mechanism allows 2 communicating hosts to agree on cryptographic algorithms & keys.
  2) Encryption of IP Datagram Payloads
  ➢ When the sender receives a segment from the transport-layer, IPsec encrypts the payload.
  ➢ The payload can only be decrypted by IPsec in the receiver.
  3) Data Integrity
  ➢ IPsec allows the receiver to verify that the datagram's header fields.
  ➢ The encrypted payload is not modified after transmission of the datagram into the n/w.
  4) Origin Authentication
  ➢ The receiver is assured that the source-address in datagram is the actual source of datagram.

3.5 Routing Algorithms
• A routing-algorithm is used to find a “good” path from source to destination.
• Typically, a good path is one that has the least cost.
• The least-cost problem: Find a path between the source and destination that has least cost.

3.5.1 Routing Algorithm Classification
• A routing-algorithm can be classified as follows:
1) Global or decentralized
2) Static or dynamic
3) Load-sensitive or Load-insensitive

3.5.1.1 Global or Decentralized
Global Routing Algorithm
• The calculation of the least-cost path is carried out at one centralized site.
• This algorithm has complete, global knowledge about the network.
• Algorithms with global state information are referred to as link-state (LS) algorithms.
Decentralized Routing Algorithm
• The calculation of the least-cost path is carried out in an iterative, distributed manner.
• No node has complete information about the costs of all network links.
• Each node has only the knowledge of the costs of its own directly attached links.
• Each node performs calculation by exchanging information with its neighboring nodes.

3.5.1.2 Static or Dynamic
Static Routing Algorithms
• Routes change very slowly over time, as a result of human intervention.
• For example: a human manually editing a router’s forwarding-table.
Dynamic Routing Algorithms
• The routing paths change, as the network-topology or traffic-loads change.
• The algorithm can be run either
→ periodically or
→ in response to topology or link cost changes.
• Advantage: More responsive to network changes.
• Disadvantage: More susceptible to routing loop problem.

3.5.1.3 Load Sensitive or Load Insensitive
Load Sensitive Algorithm
• Link costs vary dynamically to reflect the current level of congestion in the underlying link.
• If high cost is associated with congested-link, the algorithm chooses routes around congested-link.
Load Insensitive Algorithm
• Link costs do not explicitly reflect the current level of congestion in the underlying link.
• Today’s Internet routing-algorithms are load-insensitive. For example: RIP, OSPF, and BGP

3.5.2 LS Routing Algorithm

3.5.2.1 Dijkstra's Algorithm

• Dijkstra's algorithm computes the least-cost path from one node to all other nodes in the network.
• Let us define the following notation:

1) u: source-node
2) D(v): cost of the least-cost path from the source u to destination v.
3) p(v): previous node (neighbor of v) along the current least-cost path from the source to v.
4) N': subset of nodes; v is in N' if the least-cost path from the source to v is known.

Link-State (LS) Algorithm for Source Node *u*

```
Initialization:
  N' = {u}
  for all nodes v
    if v is a neighbor of u
      then D(v) = c(u,v)
    else D(v) = ∞

Loop
  find w not in N' such that D(w) is a minimum
  add w to N'
  update D(v) for each neighbor v of w and not in N':
        D(v) = min( D(v), D(w) + c(w,v) )
  /* new cost to v is either old cost to v or known
   least path cost to w plus cost from w to v */
until N'= N
```

• Example: Consider the network in Figure 3.22 and compute the least-cost paths from u to all possible destinations.

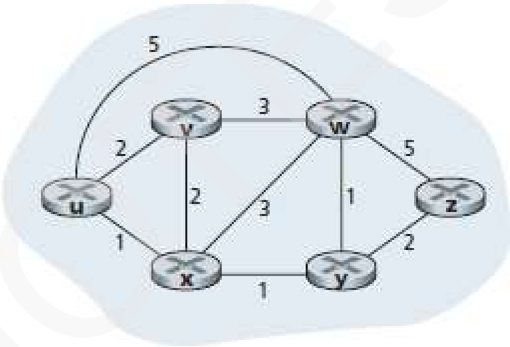


Figure 3.22: Abstract graph model of a computer network

Solution:
• Let's consider the few first steps in detail.

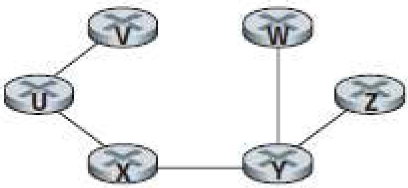
1) In the initialization step, the currently known least-cost paths from u to its directly attached neighbors, v, x, and w, are initialized to 2, 1, and 5, respectively.
2) In the first iteration, we
   → look among those nodes not yet added to the set N' and
   → find that node with the least cost as of the end of the previous iteration.
3) In the second iteration,
   → nodes v and y are found to have the least-cost paths (2) and
   → we break the tie arbitrarily and
   → add y to the set N' so that N' now contains u, x, and y.
4) And so on. . . .
5) When the LS algorithm terminates,
   We have, for each node, its predecessor along the least-cost path from the source.

• A tabular summary of the algorithm's computation is shown in Table 3.5.

step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5	uxyvwz					

Table 3.5: Running the link-state algorithm on the network in Figure 3.20

• Figure 3.23 shows the resulting least-cost paths for u for the network in Figure 3.22.



Destination	Link
v	(u, v)
w	(u, x)
x	(u, x)
y	(u, x)
z	(u, x)

Figure 3.23: Least cost path and forwarding-table for node u

3.5.3 DV Routing Algorithm

3.5.3.1 Bellman Ford Algorithm

- Distance vector (DV) algorithm is 1) iterative, 2) asynchronous, and 3) distributed.
  1) It is distributed. This is because each node
     → receives some information from one or more of its directly attached neighbors
     → performs the calculation and
     → distributes then the results of the calculation back to the neighbors.
  2) It is iterative. This is because
     → the process continues on until no more info is exchanged b/w neighbors.
  3) It is asynchronous. This is because
     → the process does not require all of the nodes to operate in lockstep with each other.
- The basic idea is as follows:
  1) Let us define the following notation:
     $D_x(y)$ = cost of the least-cost path from node x to node y, for all nodes in N.
     $D_x = [D_x(y): y \text{ in } N]$ be node x's distance vector of cost estimates from x to all other nodes y in N.
  2) Each node x maintains the following routing information:
     i) For each neighbor v, the cost c(x,v) from node x to directly attached neighbor v
     ii) Node x's distance vector, that is, $D_x = [D_x(y): y \text{ in } N]$, containing x's estimate of its cost to all destinations y in N.
     iii) The distance vectors of each of its neighbors, that is, $D_v = [D_v(y): y \text{ in } N]$ for each neighbor v of x.
  3) From time to time, each node sends a copy of its distance vector to each of its neighbors.
  4) The least costs are computed by the Bellman-Ford equation:
     $D_x(y) = \min_v\{c(x,v) + D_v(y)\}$ for each node y in N
  5) If node x's distance vector has changed as a result of this update step, node x will then send its updated distance vector to each of its neighbors.

Distance-Vector (DV) Algorithm

At each node, *x*:

```
Initialization:
   for all destinations y in N:
      Dx(y) = c(x,y)    /* if y is not a neighbor then c(x,y) = ∞ */
   for each neighbor w
      Dw(y) = ? for all destinations y in N
   for each neighbor w
      send distance vector Dx = [Dx(y): y in N] to w

loop
   wait (until I see a link cost change to some neighbor w or
         until I receive a distance vector from some neighbor w)

   for each y in N:
      Dx(y) = minv{c(x,v) + Dv(y)}

   if Dx(y) changed for any destination y
      send distance vector Dx = [Dx(y): y in N] to all neighbors

forever
```

• Figure 3.24 illustrates the operation of the DV algorithm for the simple three node network.

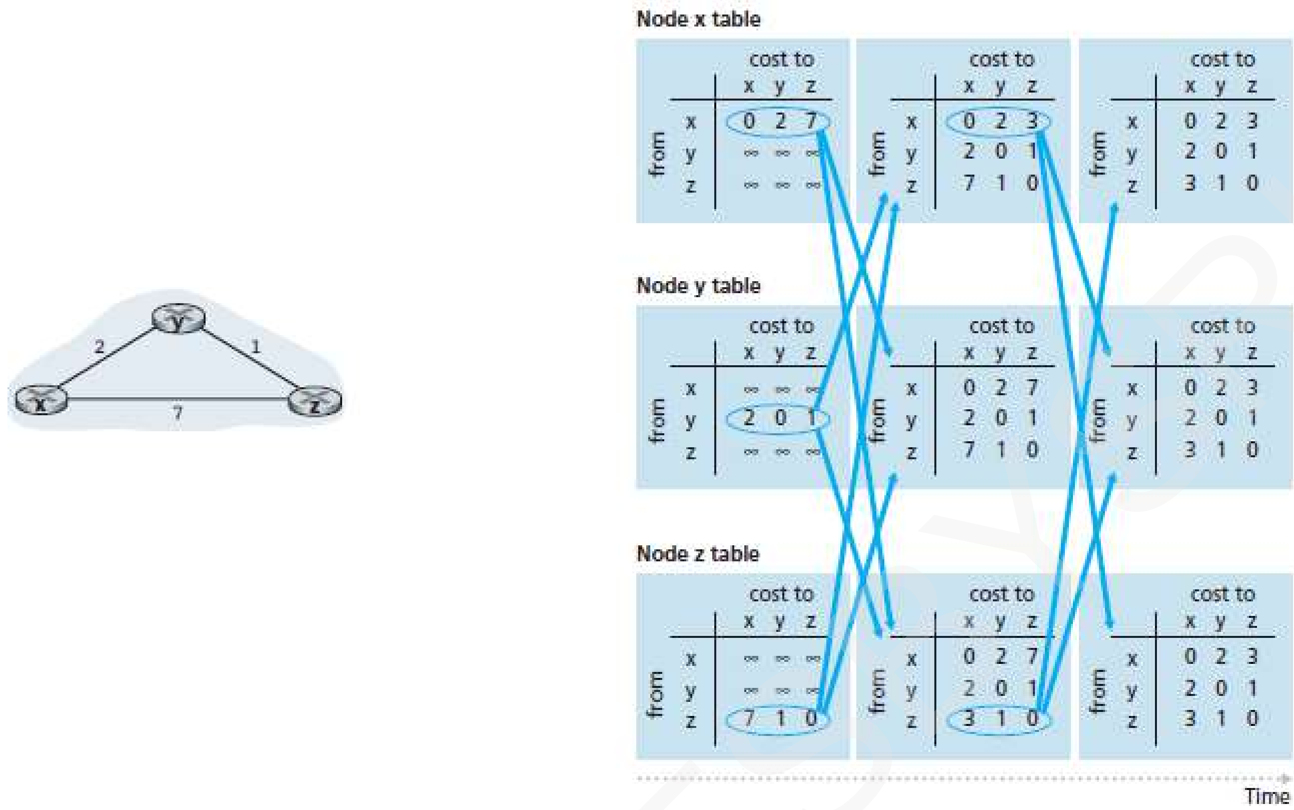


Figure 3.24: Distance-vector (DV) algorithm

• The operation of the algorithm is illustrated in a synchronous manner. Here, all nodes simultaneously

→ receive distance vectors from their neighbours

→ compute their new distance vectors, and

→ inform their neighbours if their distance vectors have changed.

• The table in the upper-left corner is node x's initial routing-table.

• In this routing-table, each row is a distance vector.

• The first row in node x's routing-table is $D_x = [D_x(x), D_x(y), D_x(z)] = [0, 2, 7]$.

• After initialization, each node sends its distance vector to each of its two neighbours.

• This is illustrated in Figure 3.24 by the arrows from the first column of tables to the second column of tables.

• For example, node x sends its distance vector Dx = [0, 2, 7] to both nodes y and z. After receiving the updates, each node recomputes its own distance vector.

• For example, node x computes

$D_x(x) = 0$

$D_x(y) = \min\{c(x,y) + D_y(y), c(x,z) + D_z(y)\} = \min\{2 + 0, 7 + 1\} = 2$

$D_x(z) = \min\{c(x,y) + D_y(z), c(x,z) + D_z(z)\} = \min\{2 + 1, 7 + 0\} = 3$

• The second column therefore displays, for each node, the node's new distance vector along with distance vectors just received from its neighbours.

• Note, that node x's estimate for the least cost to node z, $D_x(z)$, has changed from 7 to 3.

• The process of receiving updated distance vectors from neighbours, recomputing routing-table entries, and informing neighbours of changed costs of the least-cost path to a destination continues until no update messages are sent.

• The algorithm remains in the quiescent state until a link cost changes.

3.5.4 A Comparison of LS and DV Routing-algorithms

Distance Vector Protocol	Link State Protocol
Entire routing-table is sent as an update	Updates are incremental & entire routing-table is not sent as update
Distance vector protocol send periodic update at every 30 or 90 second	Updates are triggered not periodic
Updates are broadcasted	Updates are multicasted
Updates are sent to directly connected neighbour only	Update are sent to entire network & to just directly connected neighbour
Routers don't have end to end visibility of entire network.	Routers have visibility of entire network of that area only.
Prone to routing loops	No routing loops
Each node talks to only its directly connected neighbors	Each node talks with all other nodes (via broadcast)

3.5.5 Hierarchical Routing

- Two problems of a simple routing-algorithm:
    - **1) Scalability**
        - ➢ As no. of routers increases, overhead involved in computing & storing routing info increases.
    - **2) Administrative Autonomy**
        - ➢ An organization should be able to run and administer its network.
        - ➢ At the same time, the organization should be able to connect its network to internet.
- Both of these 2 problems can be solved by organizing routers into autonomous-system (AS).
- An autonomous system (AS) is a group of routers under the authority of a single administration.
  For example: same ISP or same company network.
- Two types of routing-protocol:
  1) Intra-AS routing protocol: refers to routing inside an autonomous system.
  2) Inter-AS routing protocol: refers to routing between autonomous systems.

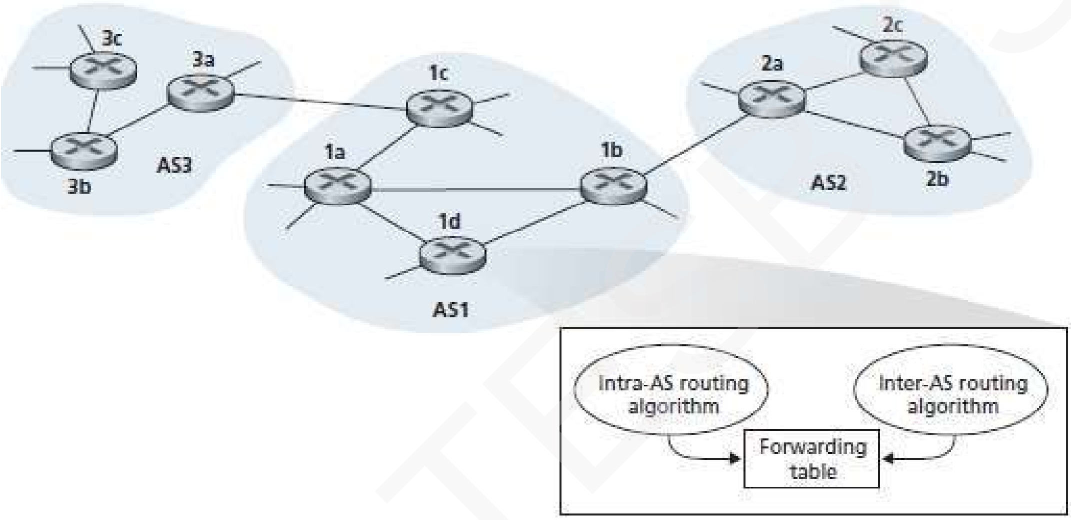


Figure 3.25: An example of interconnected autonomous-systems

3.5.5.1 Intra-AS Routing Protocol

- The routing-algorithm running within an autonomous-system is called intra-AS routing protocol.
- All routers within the same AS must run the same intra-AS routing protocol. For ex: RIP and OSPF
- Figure 3.25 provides a simple example with three ASs: AS1, AS2, and AS3.
- AS1 has four routers: 1a, 1b, 1c, and 1d. These four routers run the intra-AS routing protocol.
- Each router knows how to forward packets along the optimal path to any destination within AS1.

3.5.5.2 Intra-AS Routing Protocol

- The routing-algorithm running between 2 autonomous-systems is called inter-AS routing protocol.
- Gateway-routers are used to connect ASs to each other.
- Gateway-routers are responsible for forwarding packets to destinations outside the AS.
- Two main tasks of inter-AS routing protocol:
  1) Obtaining reachability information from neighboring Ass.
  2) Propagating the reachability information to all routers internal to the AS.
- The 2 communicating ASs must run the same inter-AS routing protocol. For ex: BGP.
- Figure 3.26 summarizes the steps in adding an outside-AS destination in a router’s forwarding-table.

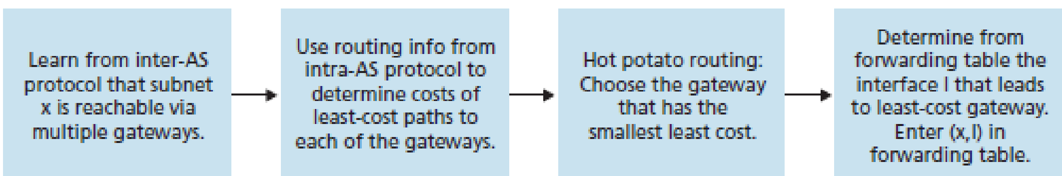


Figure 3.26: Steps in adding an outside-AS destination in a router’s forwarding-table

3.6 Routing in the Internet

- Purpose of Routing protocols:
  To determine the path taken by a datagram between source and destination.
- An autonomous-system (AS) is a collection of routers under the same administrative control.
- In AS, all routers run the same routing protocol among themselves.

3.6.1 Intra-AS Routing in the Internet: RIP

- Intra-AS routing protocols are also known as interior gateway protocols.
- An intra-AS routing protocol is used to determine how routing is performed within an AS.
- Most common intra-AS routing protocols:
  1) Routing-information Protocol (RIP) and 2) Open Shortest Path First (OSPF)
- OSPF deployed in upper-tier ISPs whereas RIP is deployed in lower-tier ISPs & enterprise-networks.

3.6.1.1 RIP Protocol

- RIP is widely used for intra-AS routing in the Internet.
- RIP is a distance-vector protocol.
- RIP uses hop count as a cost metric. Each link has a cost of 1.
- Hop count refers to the no. of subnets traversed along the shortest path from source to destination.
- The maximum cost of a path is limited to 15.
- The distance vector is the current estimate of shortest path distances from router to subnets in AS.
- Consider an AS shown in Figure 3.27.

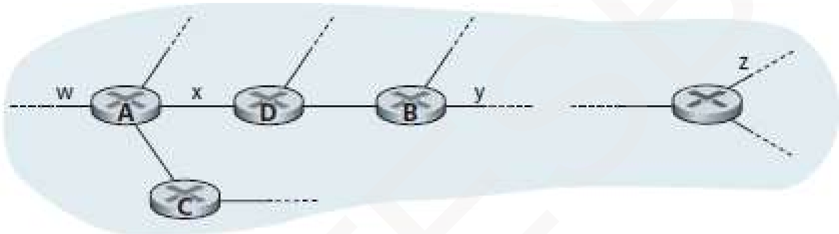


Figure 3.27: A portion of an autonomous-system

- Each router maintains a RIP table known as a routing-table.
- Figure 3.28 shows the routing-table for router D.

Destination Subnet	Next Router	Number of Hops to Destination
w	A	2
y	B	2
z	B	7
x	—	1

Figure 3.28: Routing-table in router D before receiving advertisement from router A

- Routers can send types of messages: 1) Response-message & 2) Request-message

  1) Response Message
  - ➢ Using this message, the routers exchange routing updates with their neighbors every 30 secs.
  - ➢ If a router doesn't hear from its neighbor every 180 secs, then that neighbor is not reachable.
  - ➢ When this happens, RIP
    → modifies the local routing-table and
    → propagates then this information by sending advertisements to its neighbors.
  - ➢ The response-message contains
    → list of up to 25 destination subnets within the AS and
    → sender's distance to each of those subnets.
  - ➢ Response-messages are also known as advertisements.

  2) Request Message
  - ➢ Using this message, router requests info about its neighbor's cost to a given destination.
- Both types of messages are sent over UDP using port# 520.
- The UDP segment is carried between routers in an IP datagram.

3.6.2 Intra-AS Routing in the Internet: OSPF

• OSPF is widely used for intra-AS routing in the Internet.
• OSPF is a link-state protocol that uses
  → flooding of link-state information and
  → Dijkstra least-cost path algorithm.
• Here is how it works:
  1) A router constructs a complete topological map (a graph) of the entire autonomous-system.
  2) Then, the router runs Dijkstra's algorithm to determine a shortest-path tree to all subnets.
  3) Finally, the router broadcasts link state info to all other routers in the autonomous-system.
    Specifically, the router broadcasts link state information
      → periodically at least once every 30 minutes and
      → whenever there is a change in a link's state. For ex: a change in up/down status.
• Individual link costs are configured by the network-administrator.
• OSPF advertisements are contained in OSPF messages that are carried directly by IP.
• HELLO message can be used to check whether the links are operational.
• The router can also obtain a neighboring router's database of network-wide link state.
• Some of the advanced features include:

1) Security

➢ Exchanges between OSPF routers can be authenticated.
➢ With authentication, only trusted routers can participate within an AS.
➢ By default, OSPF packets between routers are not authenticated.
➢ Two types of authentication can be configured: 1) Simple and 2) MD5.

i) Simple Authentication

¤ The same password is configured on each router.
¤ Clearly, simple authentication is not very secure.

ii) MD5 Authentication

¤ This is based on shared secret keys that are configured in all the routers.
¤ Here is how it works:
1) The sending router
  → computes a MD5 hash on the content of packet
  → includes the resulting hash value in the packet and
  → sends the packet
2) The receiving router
  → computes an MD5 hash of the packet
  → compares computed-hash value with the hash value carried in packet and
  → verifies the packet's authenticity

2) Multiple Same Cost Paths

➢ When multiple paths to a destination have same cost, OSPF allows multiple paths to be used.

3) Integrated Support for Unicast & Multicast Routing

➢ Multicast OSPF (MOSPF) provides simple extensions to OSPF to provide for multicast-routing.
➢ MOSPF
  → uses the existing OSPF link database and
  → adds a new type of link-state advertisement to the existing broadcast mechanism.

4) Support for Hierarchy within a Single Routing Domain

➢ An autonomous-system can be configured hierarchically into areas.
➢ In area, an area-border-router is responsible for routing packets outside the area.
➢ Exactly one OSPF area in the AS is configured to be the backbone-area.
➢ The primary role of the backbone-area is to route traffic between the other areas in the AS.

3.6.3 Inter-AS Routing: BGP

• BGP is widely used for inter-AS routing in the Internet.
• Using BGP, each AS can
  1) Obtain subnet reachability-information from neighboring ASs.
  2) Propagate the reachability-information to all routers internal to the AS.
  3) Determine good routes to subnets based on i) reachability-information and ii) AS policy.
• Using BGP, each subnet can advertise its existence to the rest of the Internet.

3.6.3.1 Basics

• Pairs of routers exchange routing-information over semi-permanent TCP connections using port-179.
• One TCP connection is used to connect 2 routers in 2 different autonomous-systems.
  Semipermanent TCP connection is used to connect among routers within an autonomous-system.
• Two routers at the end of each connection are called peers.
  The messages sent over the connection is called a session.
• Two types of session:
  1) External BGP (eBGP) session
  ➢ This refers to a session that spans 2 autonomous-systems.
  2) Internal BGP (iBGP) session
  ➢ This refers to a session between routers in the same AS.

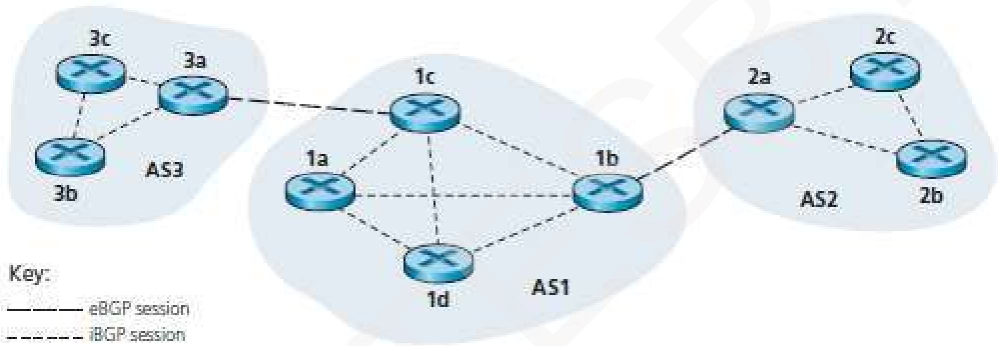


Figure 3.29: eBGP and iBGP sessions

• BGP operation is shown in Figure 3.29.
• The destinations are not hosts but instead are CIDRized prefixes.
• Each prefix represents a subnet or a collection of subnets.

3.6.3.2 Path Attributes & Routes

• An autonomous-system is identified by its globally unique ASN (Autonomous-System Number).
• A router advertises a prefix across a session.
• The router includes a number of attributes with the prefix.
• Two important attributes: 1) AS-PATH and 2) NEXT-HOP

1) AS-PATH
  ➢ This attribute contains the ASs through which the advertisement for the prefix has passed.
  ➢ When a prefix is passed into an AS, the AS adds its ASN to the ASPATH attribute.
  ➢ Routers use the AS-PATH attribute to detect and prevent looping advertisements.
  ➢ Routers also use the AS-PATH attribute in choosing among multiple paths to the same prefix.

2) NEXT-HOP
  ➢ This attribute provides the critical link between the inter-AS and intra-AS routing protocols.
  ➢ This attribute is the router-interface that begins the AS-PATH.

• BGP also includes
  → attributes which allow routers to assign preference-metrics to the routes.
  → attributes which indicate how the prefix was inserted into BGP at the origin AS.
• When a gateway-router receives a route-advertisement, the gateway-router decides
  → whether to accept or filter the route and
  → whether to set certain attributes such as the router preference metrics.

3.6.3.3 Route Selection

• For 2 or more routes to the same prefix, the following elimination-rules are invoked sequentially:

1) Routes are assigned a local preference value as one of their attributes.
2) The local preference of a route
   → will be set by the router or
   → will be learned by another router in the same AS.
3) From the remaining routes, the route with the shortest AS-PATH is selected.
4) From the remaining routes, the route with the closest NEXT-HOP router is selected.
5) If more than one route still remains, the router uses BGP identifiers to select the route.

3.6.3.4 Routing Policy

• Routing policy is illustrated as shown in Figure 3.30.
• Let A, B, C, W, X & Y = six interconnected autonomous-systems.
  W, X & Y = three stub-networks.
  A, B & C = three backbone provider networks.
• All traffic entering a stub-network must be destined for that network.
  All traffic leaving a stub-network must have originated in that network.
• Clearly, W and Y are stub-networks.
• X is a multihomed stub-network, since X is connected to the rest of the n/w via 2 different providers
• X itself must be the source/destination of all traffic leaving/entering X.
• X will function as a stub-network if X has no paths to other destinations except itself.
• There are currently no official standards that govern how backbone ISPs route among themselves.

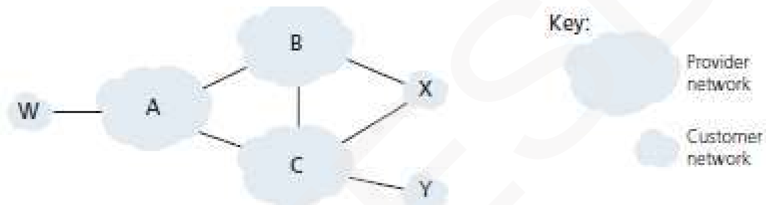


Figure 3.30: A simple BGP scenario

3.7 Broadcast & Multicast Routing
3.7.1 Broadcast Routing Algorithms
• Broadcast-routing means delivering a packet from a source-node to all other nodes in the network.

3.7.1.1 N-way Unicast
• Given N destination-nodes, the source-node
→ makes N copies of the packet and
→ transmits then the N copies to the N destinations using unicast routing (Figure 3.31).
• Disadvantages:
1) Inefficiency
➢ If source is connected to the n/w via single link, then N copies of packet will traverse this link.
2) More Overhead & Complexity
➢ An implicit assumption is that the sender knows broadcast recipients and their addresses.
➢ Obtaining this information adds more overhead and additional complexity to a protocol.
3) Not suitable for Unicast Routing
➢ It is not good idea to depend on the unicast routing infrastructure to achieve broadcast.

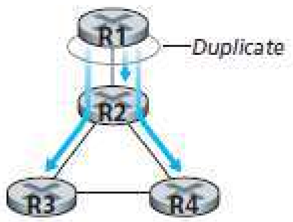


Figure 3.31: Duplicate creation/transmission

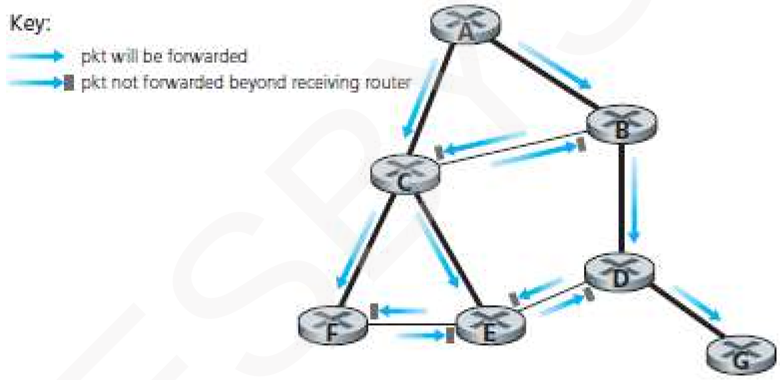


Figure 3.32: Reverse path forwarding

3.7.1.2 Uncontrolled Flooding
• The source-node sends a copy of the packet to all the neighbors.
• When a node receives a broadcast-packet, the node duplicates & forwards packet to all neighbors.
• In connected-graph, a copy of the broadcast-packet is delivered to all nodes in the graph.
• Disadvantages:
1) If the graph has cycles, then copies of each broadcast-packet will cycle indefinitely.
2) When a node is connected to 2 other nodes, the node creates & forwards multiple copies of packet
• Broadcast-storm refers to
"The endless multiplication of broadcast-packets which will eventually make the network useless."

3.7.1.3 Controlled Flooding
• A node can avoid a broadcast-storm by judiciously choosing
→ when to flood a packet and when not to flood a packet.
• Two methods for controlled flooding:
1) Sequence Number Controlled Flooding
➢ A source-node
→ puts its address as well as a broadcast sequence-number into a broadcast-packet
→ sends then the packet to all neighbors.
➢ Each node maintains a list of the source-address & sequence# of each broadcast-packet.
➢ When a node receives a broadcast-packet, the node checks whether the packet is in this list.
➢ If so, the packet is dropped; if not, the packet is duplicated and forwarded to all neighbors.
2) Reverse Path Forwarding (RPF)
➢ If a packet arrived on the link that has a path back to the source;
Then the router transmits the packet on all outgoing-links.
Otherwise, the router discards the incoming-packet.
➢ Such a packet will be dropped. This is because
→ the router has already received a copy of this packet (Figure 3.32).

3.7.1.4 Spanning - Tree Broadcast

- This is another approach to providing broadcast. (MST → Minimum Spanning Tree).
- Spanning-tree is a tree that contains each and every node in a graph.
- A spanning-tree whose cost is the minimum of all of the graph's spanning-trees is called a MST.
- Here is how it works (Figure 3.33):
  1) Firstly, the nodes construct a spanning-tree.
  2) The node sends broadcast-packet out on all incident links that belong to the spanning-tree.
  3) The receiving-node forwards the broadcast-packet to all neighbors in the spanning-tree.

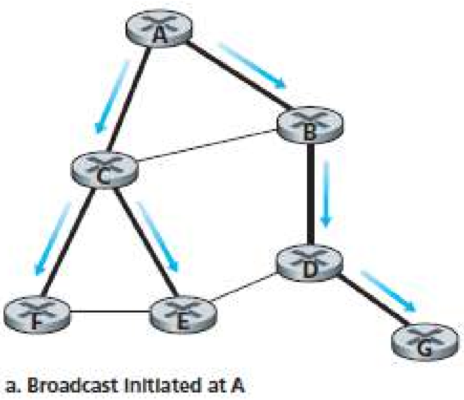


Figure 3.33: Broadcast along a spanning-tree

- Disadvantage:
  Complex: The main complexity is the creation and maintenance of the spanning-tree.

3.7.1.4.1 Center Based Approach

- This is a method used for building a spanning-tree.
- Here is how it works:
  1) A center-node (rendezvous point or a core) is defined.
  2) Then, the nodes send unicast tree-join messages to the center-node.
  3) Finally, a tree-join message is forwarded toward the center until the message either
     → arrives at a node that already belongs to the spanning-tree or
     → arrives at the center.
- Figure 3.34 illustrates the construction of a center-based spanning-tree.

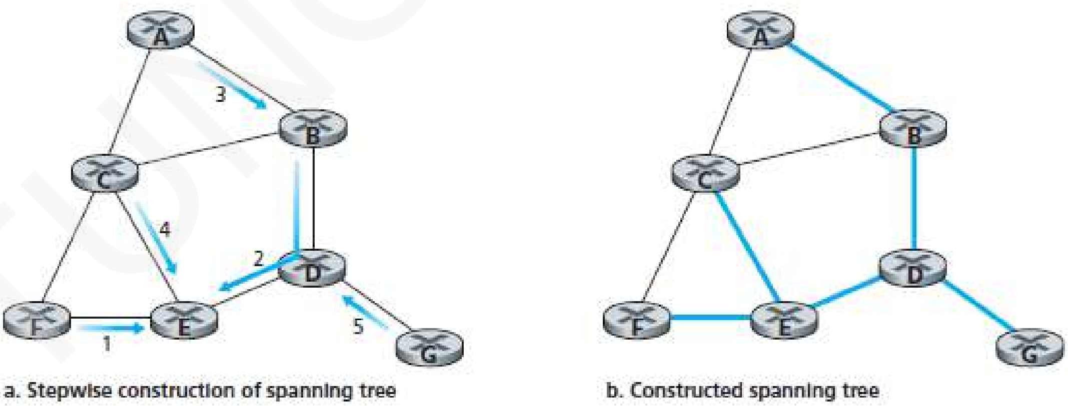


Figure 3.34: Center-based construction of a spanning-tree

3.7.2 Multicast

- Multicasting means a multicast-packet is delivered to only a subset of network-nodes.
- A number of emerging network applications requires multicasting. These applications include
  1) Bulk data transfer (for ex: the transfer of a software upgrade)
  2) Streaming continuous media (for ex: the transfer of the audio/video)
  3) Shared data applications (for ex: a teleconferencing application)
  4) Data feeds (for ex: stock quotes)
  5) Web cache updating and
  6) Interactive gaming (for ex: multiplayer games).
- Two problems in multicast communication:
  1) How to identify the receivers of a multicast-packet.
  2) How to address a packet sent to these receivers.
- A multicast-packet is addressed using address indirection.
- A single identifier is used for the group of receivers.
- Using this single identifier, a copy of the packet is delivered to all multicast receivers.
- In the Internet, class-D IP address is the single identifier used to represent a group of receivers.
- The multicast-group abstraction is illustrated in Figure 3.35.

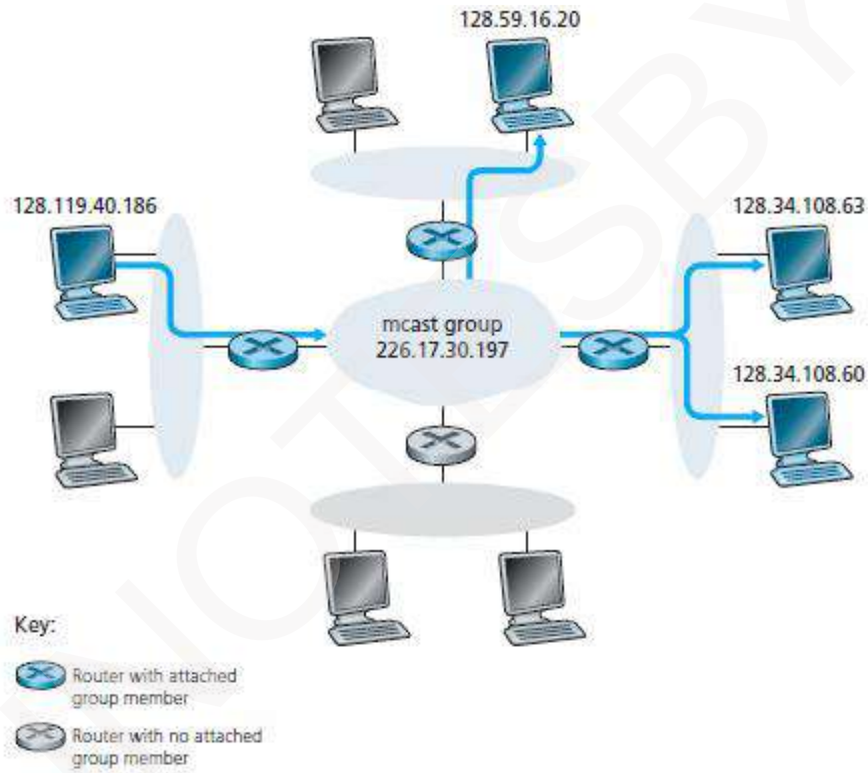


Figure 3.35: The multicast group: A datagram addressed to the group is delivered to all members of the multicast group

3.7.2.1 IGMP

• In the Internet, the multicast consists of 2 components:

1) IGMP (Internet Group Management Protocol)

➢ IGMP is a protocol that manages group membership.

➢ It provides multicast-routers info about the membership-status of hosts connected to the n/w

➢ The operations are i) Joining/Leaving a group and ii) monitoring membership

2) Multicast Routing Protocols

➢ These protocols are used to coordinate the multicast-routers throughout the Internet.

➢ A host places a multicast address in the destination address field to send packets to a set of hosts belonging to a group.

• The IGMP protocol operates between a host and its attached-router.

• Figure 3.36 shows three first-hop multicast-routers.

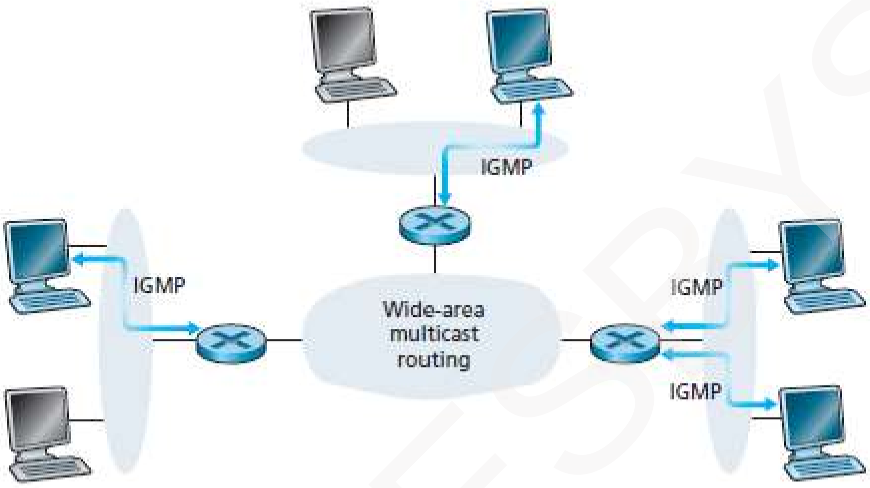


Figure 3.36: The two components of network-layer multicast in the Internet: IGMP and multicast-routing protocols

• IGMP messages are encapsulated within an IP datagram.

• Three types of message: 1) membership_query 2) membership_report 3) leave_group

1) membership_query

➢ A host sends a membership-query message to find active group-members in the network.

2) membership_report

➢ A host sends membership_report message when an application first joins a multicast-group.

➢ The host sends this message w/o waiting for a membership_query message from the router.

3) leave_group

➢ This message is optional.

➢ The host sends this message to leave the multicast-group.

• How does a router detect when a host leaves the multicast-group?

Answer: The router infers that a host is no longer in the multicast-group if it no longer responds to a membership_query message. This is called soft state.

3.7.2.2 Multicast Routing Algorithms

• The multicast-routing problem is illustrated in Figure 3.37.
• Two methods used for building a multicast-routing tree:
  1) Single group-shared tree.
  2) Source-specific routing tree.

1) Multicast Routing using a Group Shared Tree

• A single group-shared tree is used to distribute the traffic for all senders in the group.
• This is based on
  Building a tree that includes all edge-routers & attached-hosts belonging to the multicast-group.
• In practice, a center-based approach is used to construct the multicast-routing tree.
• Edge-routers send join messages addressed to the center-node.
• Here is how it works:
  1) A center-node (rendezvous point or a core) is defined.
  2) Then, the edge-routers send unicast tree-join messages to the center-node.
  3) Finally, a tree-join message is forwarded toward the center until it either
    → arrives at a node that already belongs to the multicast tree or
    → arrives at the center.

2) Multicast Routing using a Source Based Tree

• A source-specific routing tree is constructed for each individual sender in the group.
• In practice, an RPF algorithm is used to construct a multicast forwarding tree.
• The solution to the problem of receiving unwanted multicast-packets under RPF is known as pruning.
• A multicast-router that has no attached-hosts will send a prune message to its upstream router.

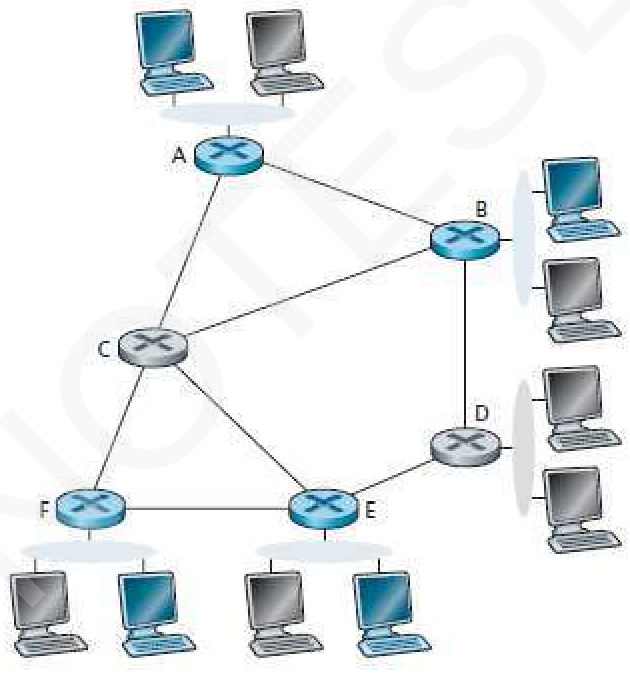


Figure 3.37: Multicast hosts, their attached routers, and other routers

3.7.2.3 Multicast Routing in the Internet

• Three multicast routing protocols are:

1) Distance Vector Multicast Routing Protocol (DVMRP)
2) Protocol Independent Multicast (PIM) and
3) Source Specific Multicast (SSM)

1) DVMRP

• DVMRP was the first multicast-routing protocol used in the Internet.
• DVMRP uses an RPF algorithm with pruning. (Reverse Path Forwarding).

2) PIM

• PIM is the most widely used multicast-routing protocol in the Internet.
• PIM divides multicast routing into sparse and dense mode.

i) Dense Mode

- Group-members are densely located.
- Most of the routers in the area need to be involved in routing the data.
- PIM dense mode is a flood-and-prune reverse path forwarding technique.

i) Sparse Mode

- The no. of routers with attached group-members is small with respect to total no. of routers.
- Group-members are widely dispersed.
- This uses rendezvous points to set up the multicast distribution tree.

3) SSM

• Only a single sender is allowed to send traffic into the multicast tree. This simplifies tree construction & maintenance.

MODULE-WISE QUESTIONS

PART 1

1) List out network-layer services. (2)
2) With a diagram, explain virtual circuit network. (6*)
3) With a diagram, explain datagram network. (6*)
4) Compare datagram & virtual-circuit networks. (4*)
5) With a diagram, explain 4 components of router. (6*)
6) With a diagram for each, explain 3 types of switching fabrics. (8*)
7) Briefly explain IP & its services. (4*)
8) With general format, explain various field of IPv4. (8*)
9) Explain fragmentation. Explain 3 fields related to fragmentation (6*)
10) Briefly explain IPv4 addressing. (8)
11) With a diagram, explain subnet addressing. (6*)
12) With a diagram, explain the working of DHCP. (6*)
13) With a diagram, explain the working of NAT. (6*)
14) Briefly explain ICMP. (8)
15) Explain changes from IPv4 to IPv6. (4*)
16) With general format, explain various field of IPv6. (8*)
17) Briefly explain IPv4 fields not present in IPv6. (4)
18) Compare IPv4 & IPv6. (4*)
19) Explain 2 strategies to make transition from IPv4 to IPv6. (8*)
20) Briefly explain IPSec & its services. (6)

PART 2

21) Define routing algorithm. Explain 3 classification of routing algorithm. (6*)
22) Explain Dijkstra's algorithm with example. (8*)
23) Explain Bellman-Ford algorithm with example. (8*)
24) Compare distance vector & link state protocols. (4*)
25) Explain the intra-AS and inter-AS routing protocols. (4*)
26) With a diagram, explain the working of RIP. (6*)
27) With a diagram, explain the working of OSPF. (6*)
28) With a diagram, explain the working of BGP. (8*)
29) What are disadvantages of N-way Unicast and Uncontrolled Flooding? (4)
30) Explain the following broadcast routing algorithms: (8*)
    i) Controlled flooding
    ii) Spanning - tree broadcast
31) Briefly explain multicasting & its applications. (4)
32) Briefly explain the working of IGMP. (4)
33) Briefly explain two methods used for building a multicast-routing tree. (6*)
34) Briefly explain three multicast routing protocols. (4)