Capítol 3. Core Network

3.1 Nivell d'enllaç

3.2 Control de la congestió i QoS

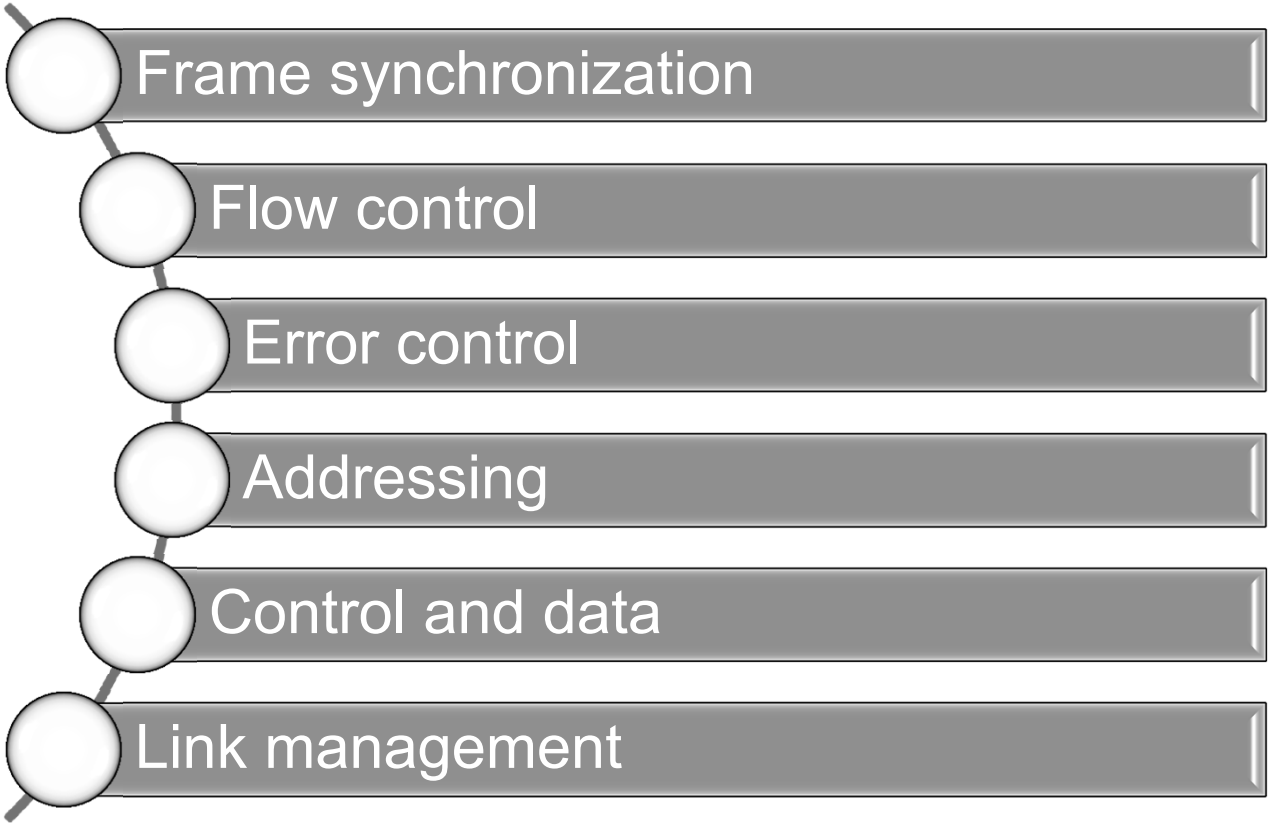
3.3 Commutació d'etiquetes MPLS

3.4 Software Defined Networking (SDN)

3.1 Nivell d'enllaç

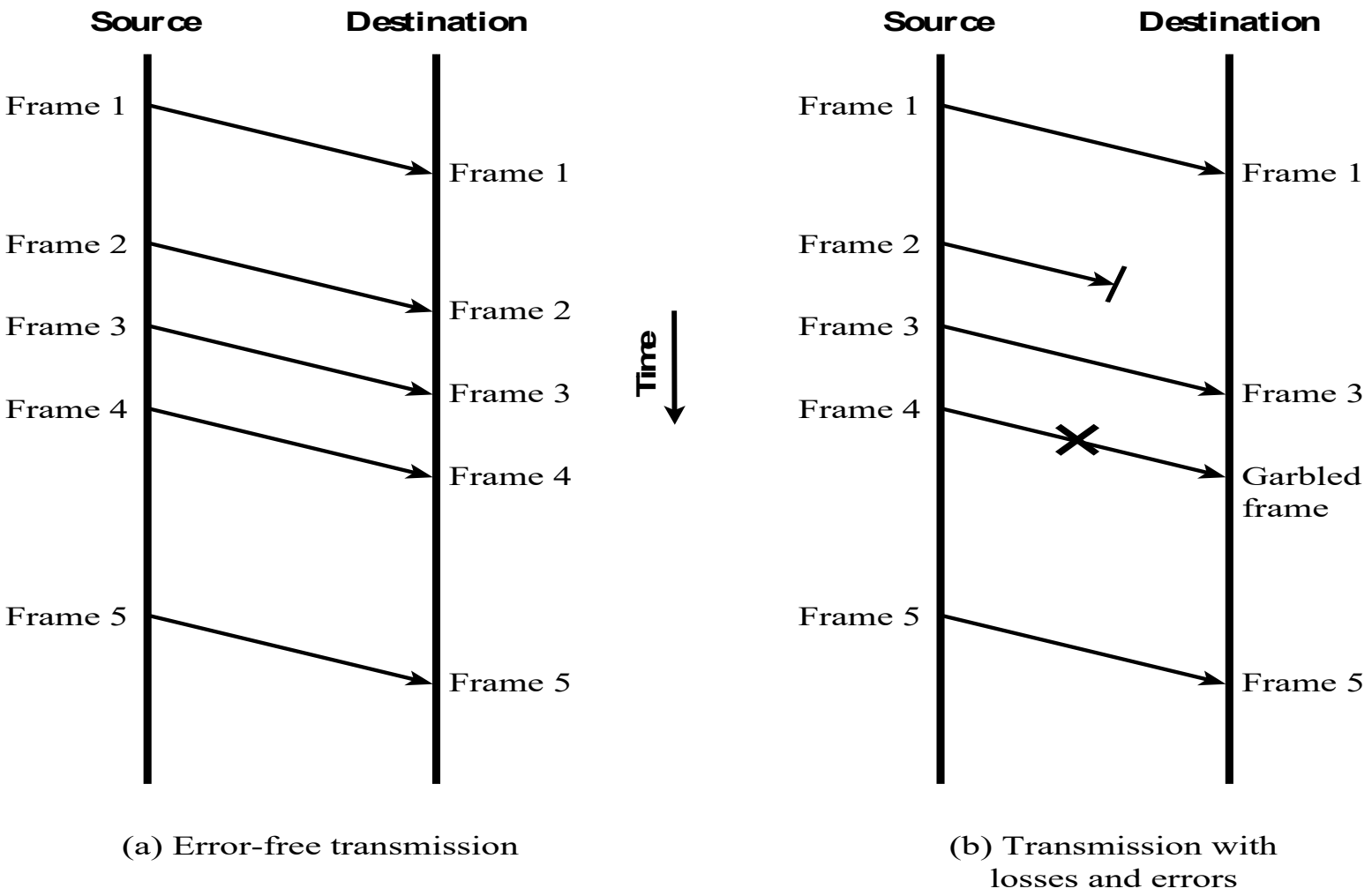
Data Link Control Protocols

- Requirements and objectives for effective data communication between two directly connected transmitting-receiving stations:



Flow Control

- Technique for assuring that a transmitting entity does not over-whelm a receiving entity with data
  - The receiving entity typically allocates a data buffer of some maximum length for a transfer
  - When data are received, the receiver must do a certain amount of processing before passing the data to the higher-level software
- In the absence of flow control, the receiver's buffer may fill up and overflow while it is processing old data



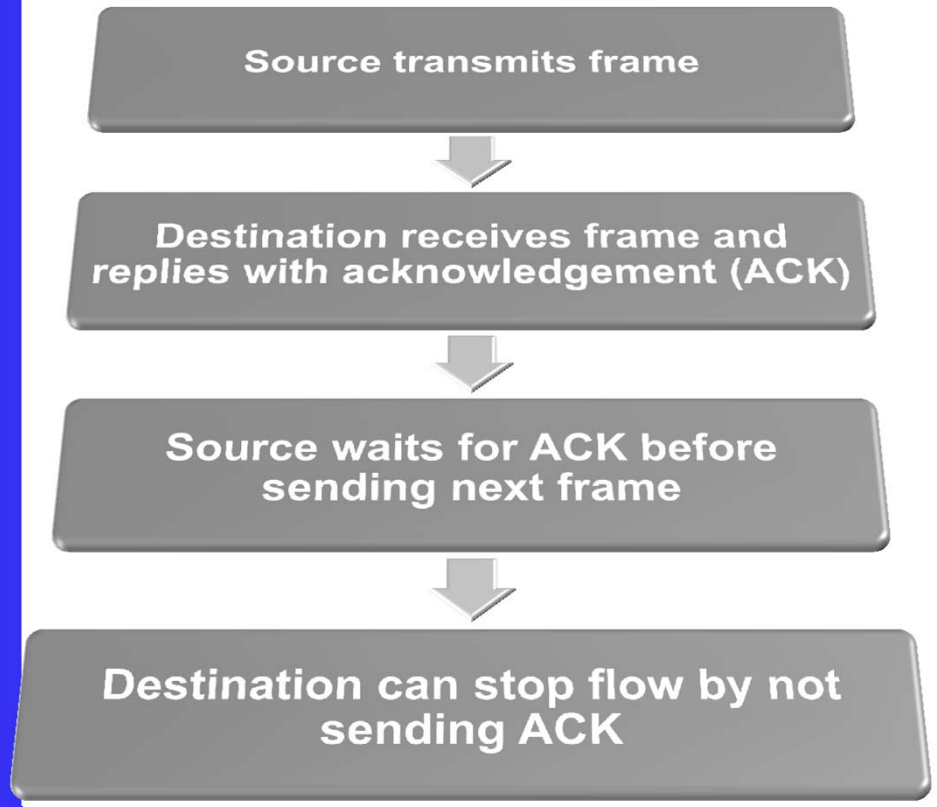
(a) Error-free transmission

(b) Transmission with losses and errors

Figure 7.1 Model of Frame Transmission

Stop-and-Wait Flow Control

- Simplest form of flow control



- It is often the case that a source will break up a large block of data into smaller blocks and transmit the data in many frames
  - The buffer size of the receiver may be limited
  - The longer the transmission, the more likely that there will be an error, necessitating retransmission of the entire frame
  - On a shared medium it is usually desirable not to permit one station to the medium for an extended period, thus causing long delays at the other sending station

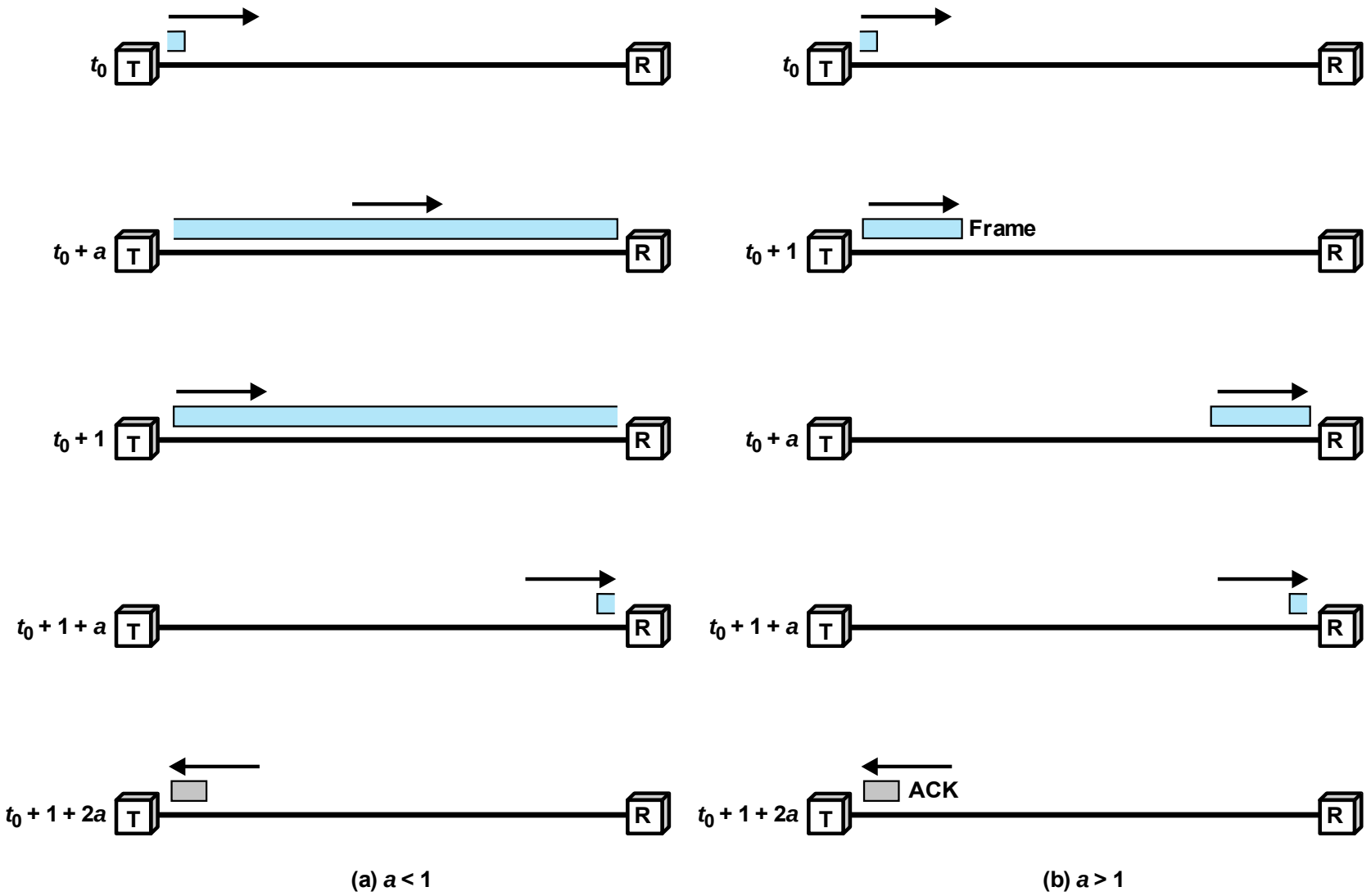


Figure 7.2 Stop-and-Wait Link Utilization (transmission time = 1; propagation time = *a*)

$$\alpha = \frac{B}{L}$$

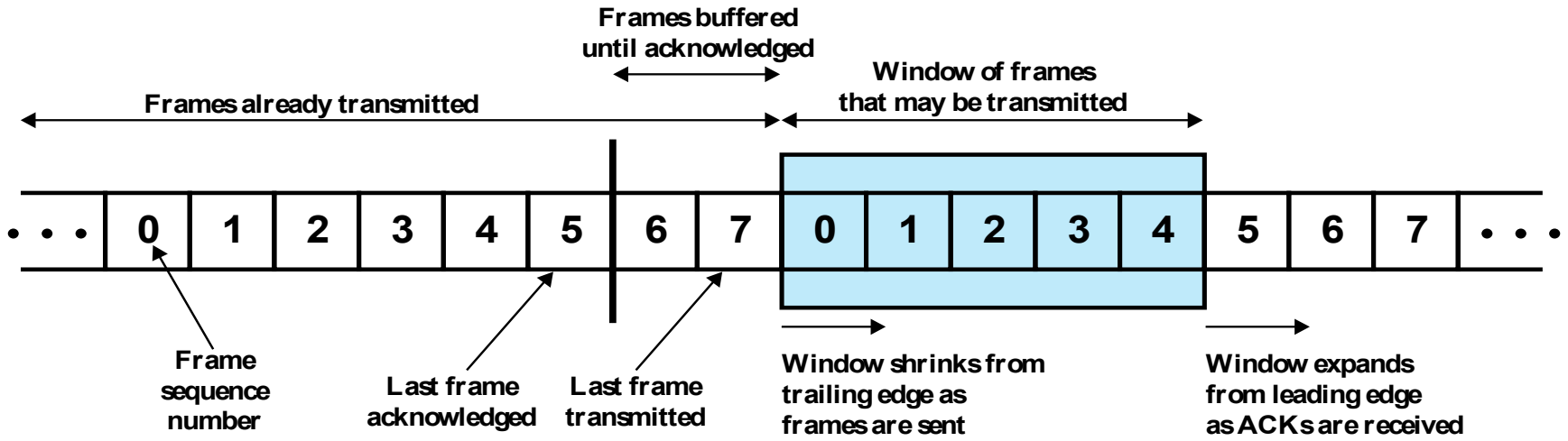
B = bits del LINK

L = bits de la trama

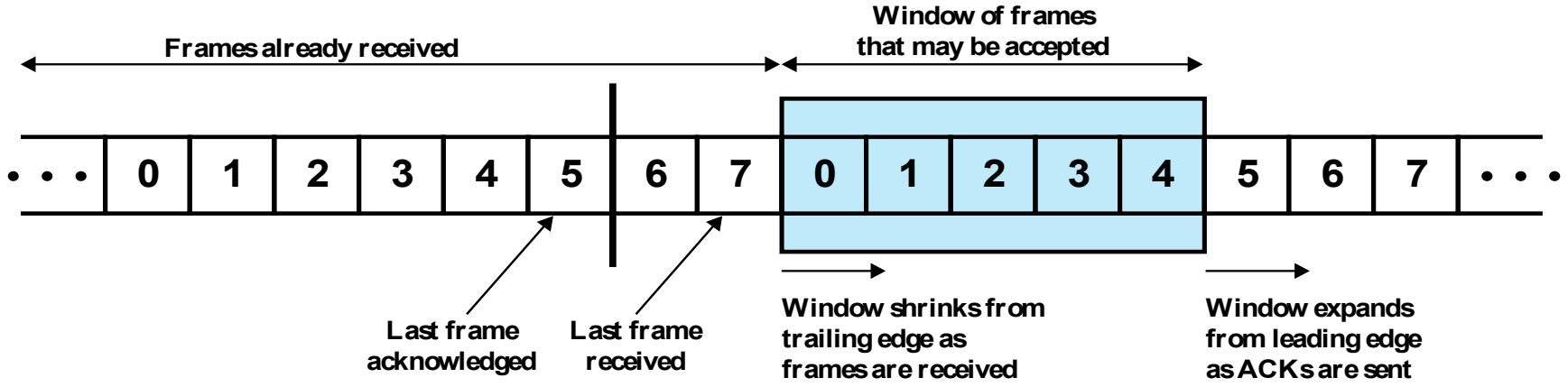
$$\frac{V_p}{V_t} = \frac{\text{Km/s}}{\text{b/s}} = \frac{\text{Km}}{\text{b}} \quad \text{ft} \quad \frac{\text{b}}{\text{Km}} = \frac{V_t}{V_p}$$

Sliding Windows Flow Control

- Allows multiple numbered frames to be in transit
  - Receiver has buffer W long
  - Transmitter sends up to W frames without ACK
  - ACK includes number of next frame expected
  - Sequence number is bounded by size of field (k)
    - *Frames are numbered modulo 2^k*
    - *Giving max window size of up to $2^k - 1$*
  - Receiver can ACK frames without permitting further transmission (Receive Not Ready)
  - Must send a normal acknowledge to resume
- If have full-duplex link, can piggyback ACKs



(a) Sender's perspective



(b) Receiver's perspective

Figure 7.3 Sliding-Window Depiction

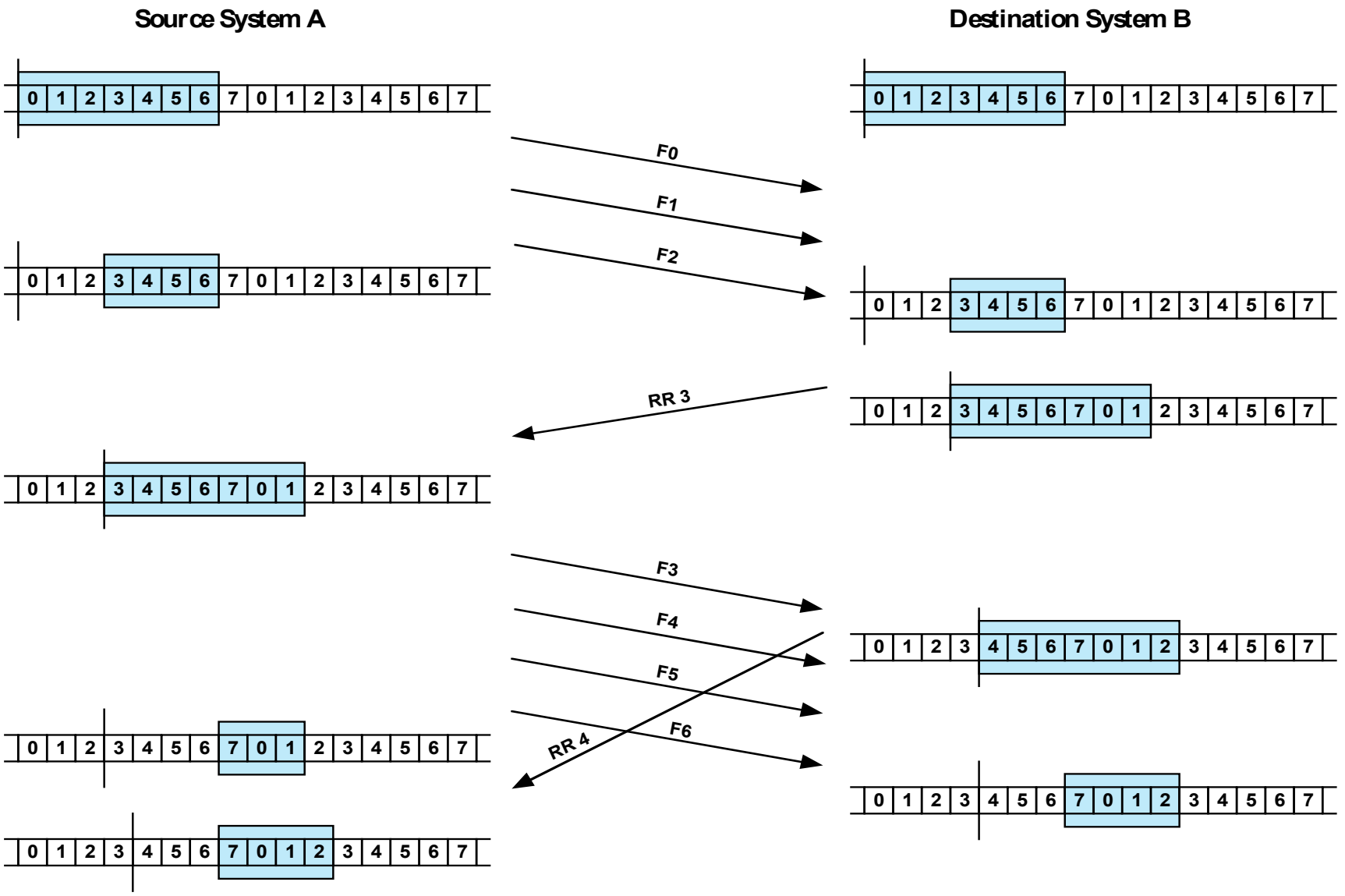
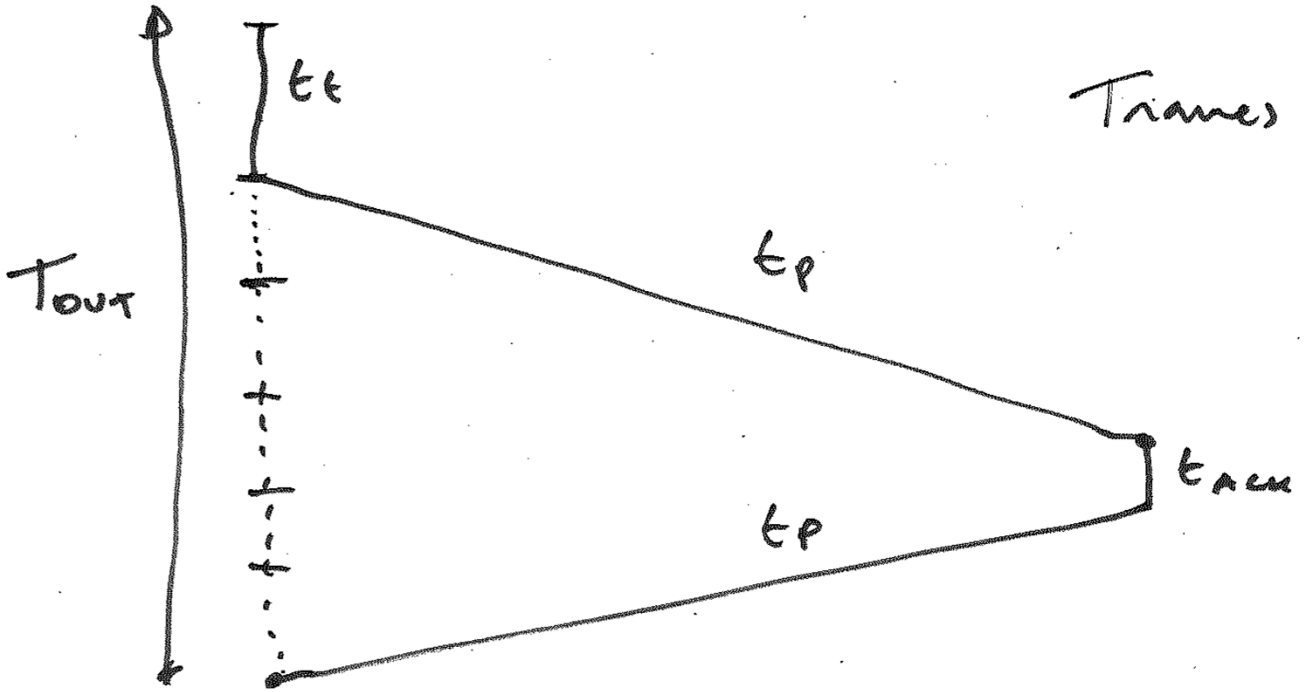


Figure 7.4 Example of a Sliding-Window Protocol

FINESTRA

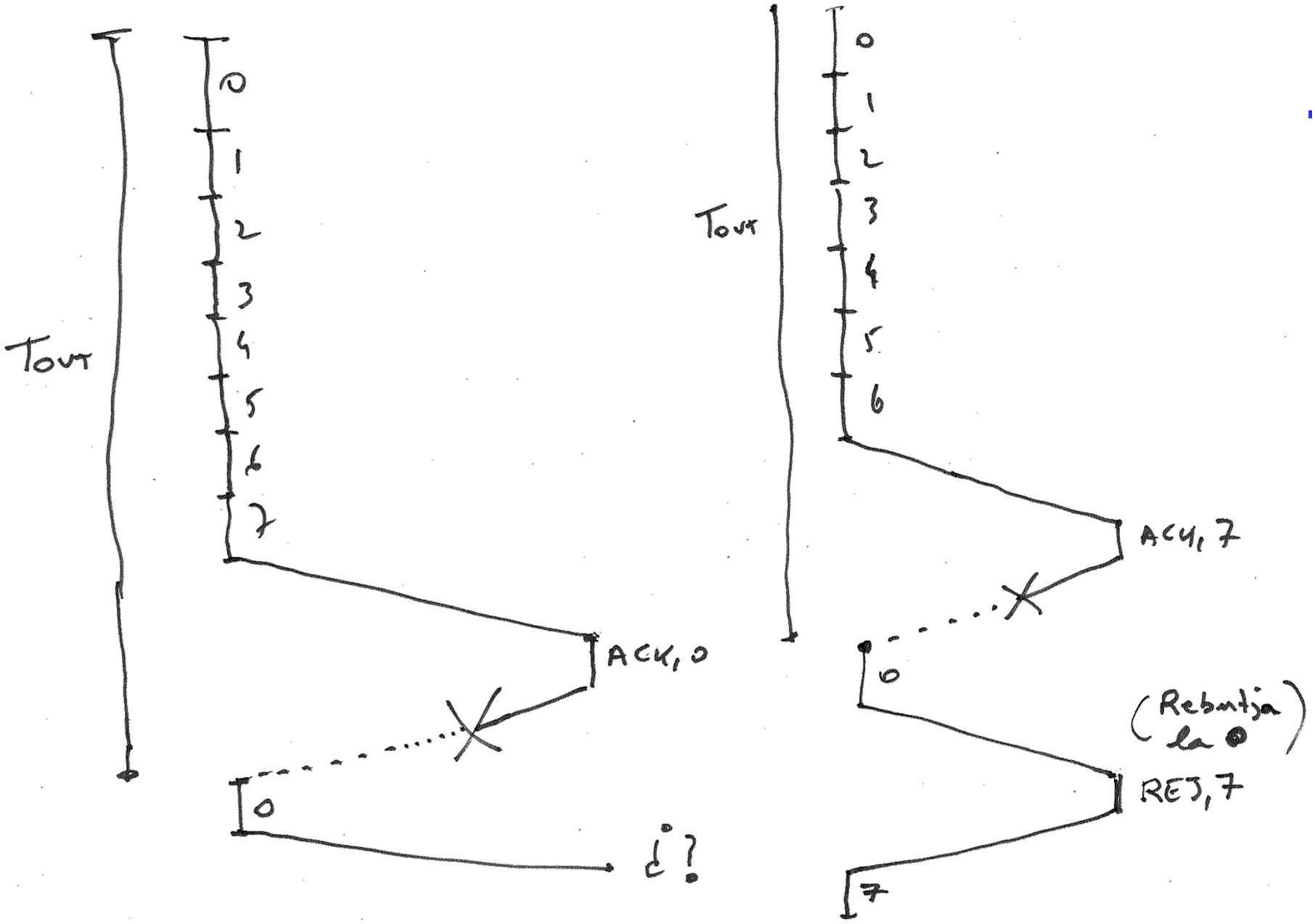


Trames iguals (mitjana)

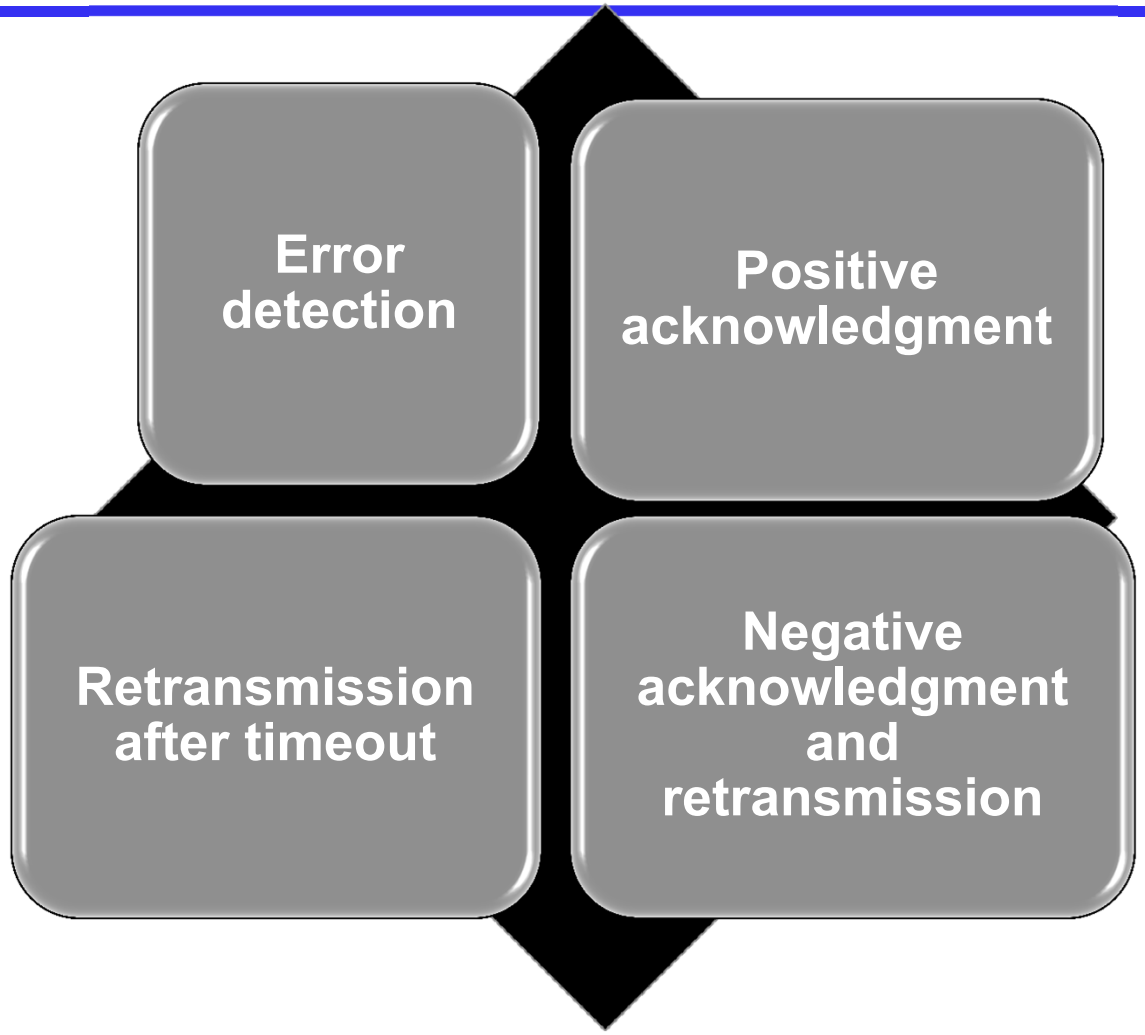
$$T_{OUT\,mínim} = t_t + t_p + t_{acm} + t_p$$

$$\#\ \text{FINESTRA ÒPTIM} = \frac{T_{OUT}}{t_t}$$

Finestra: # trames pendent de confirmar Màx $2^k - 1$ (GO-BACK-N)



Error Control Techniques



Lost frames

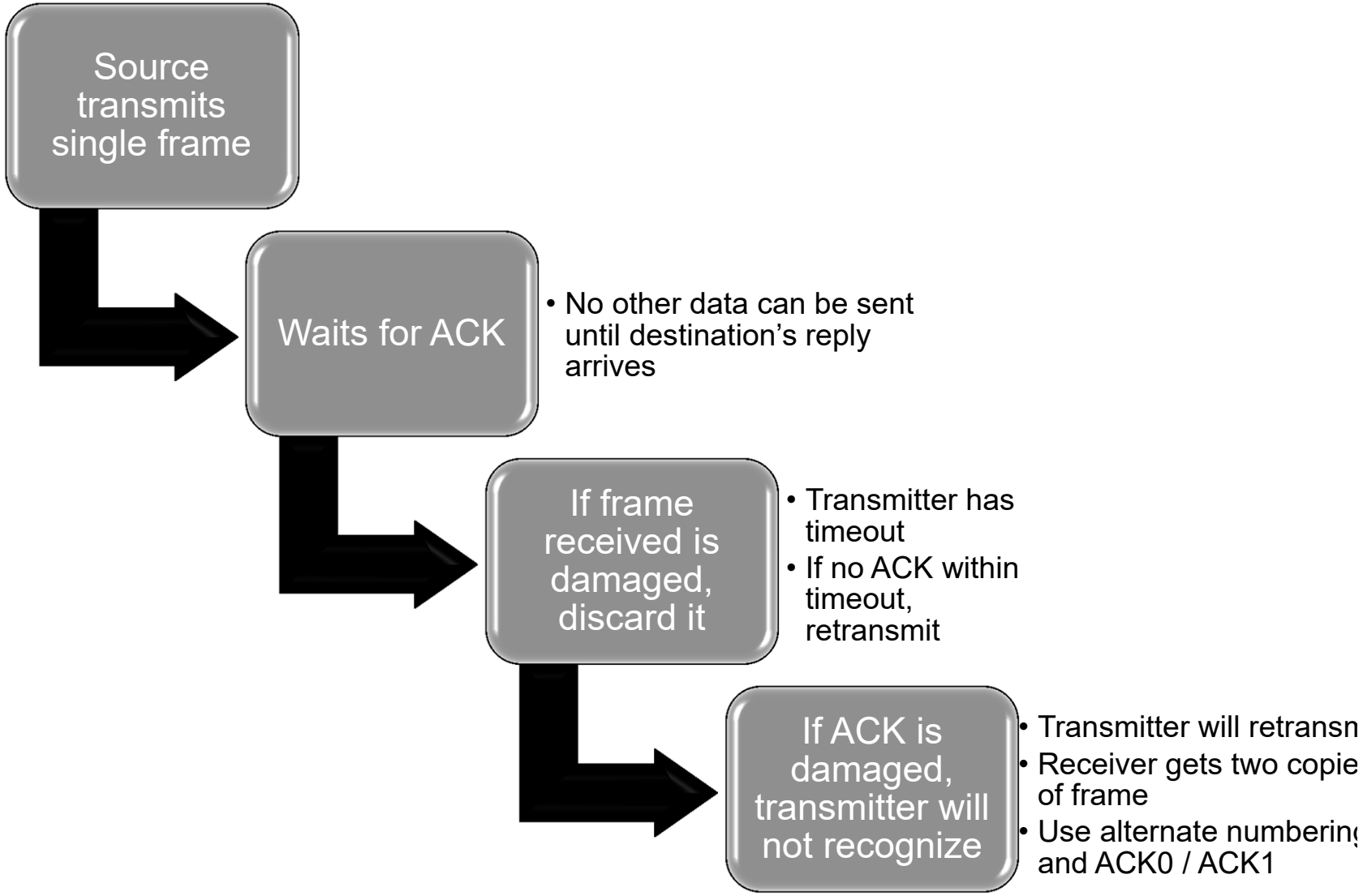
- a frame fails

to arrive at the other side

Damaged frames

- frame arrives but some of the bits are in error

Stop and Wait ARQ



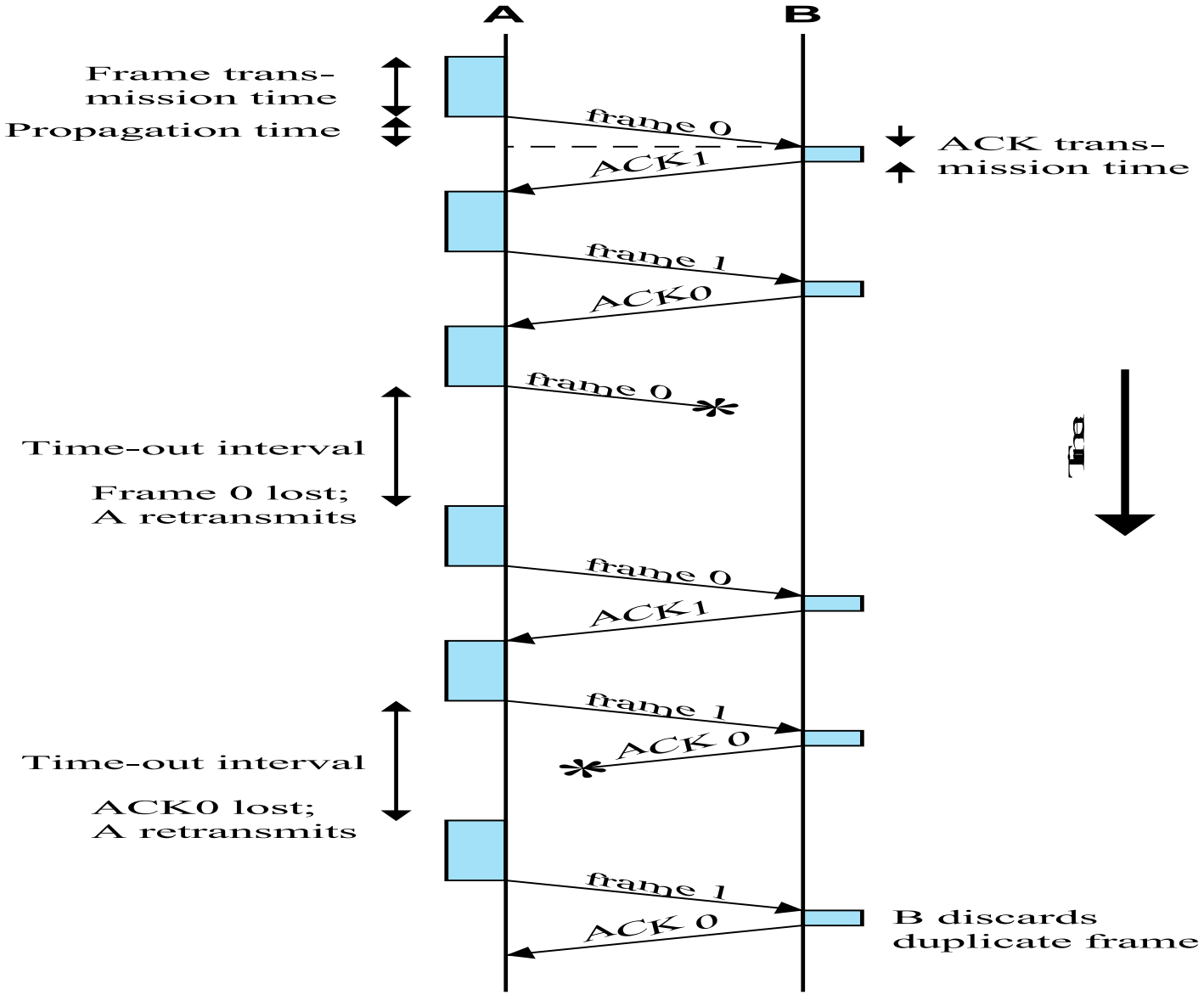


Figure 7.5 Stop-and-Wait ARQ

Go-Back-N ARQ

- Most commonly used error control
- Based on sliding-window
- Use window size to control number of outstanding frames
- While no errors occur, the destination will acknowledge incoming frames as usual
  - RR=receive ready, or piggybacked acknowledgment
- If the destination station detects an error in a frame, it may send a negative acknowledgment
  - REJ=reject
  - Destination will discard that frame and all future frames until the frame in error is received correctly
  - Transmitter must go back and retransmit that frame and all subsequent frames

Selective-Reject (ARQ)

- Also called selective retransmission
- Only rejected frames are retransmitted
- Subsequent frames are accepted by the receiver and buffered
- Minimizes retransmission
- Receiver must maintain large enough buffer
- More complex logic in transmitter
  - Less widely used
- Useful for satellite links with long propagation delays

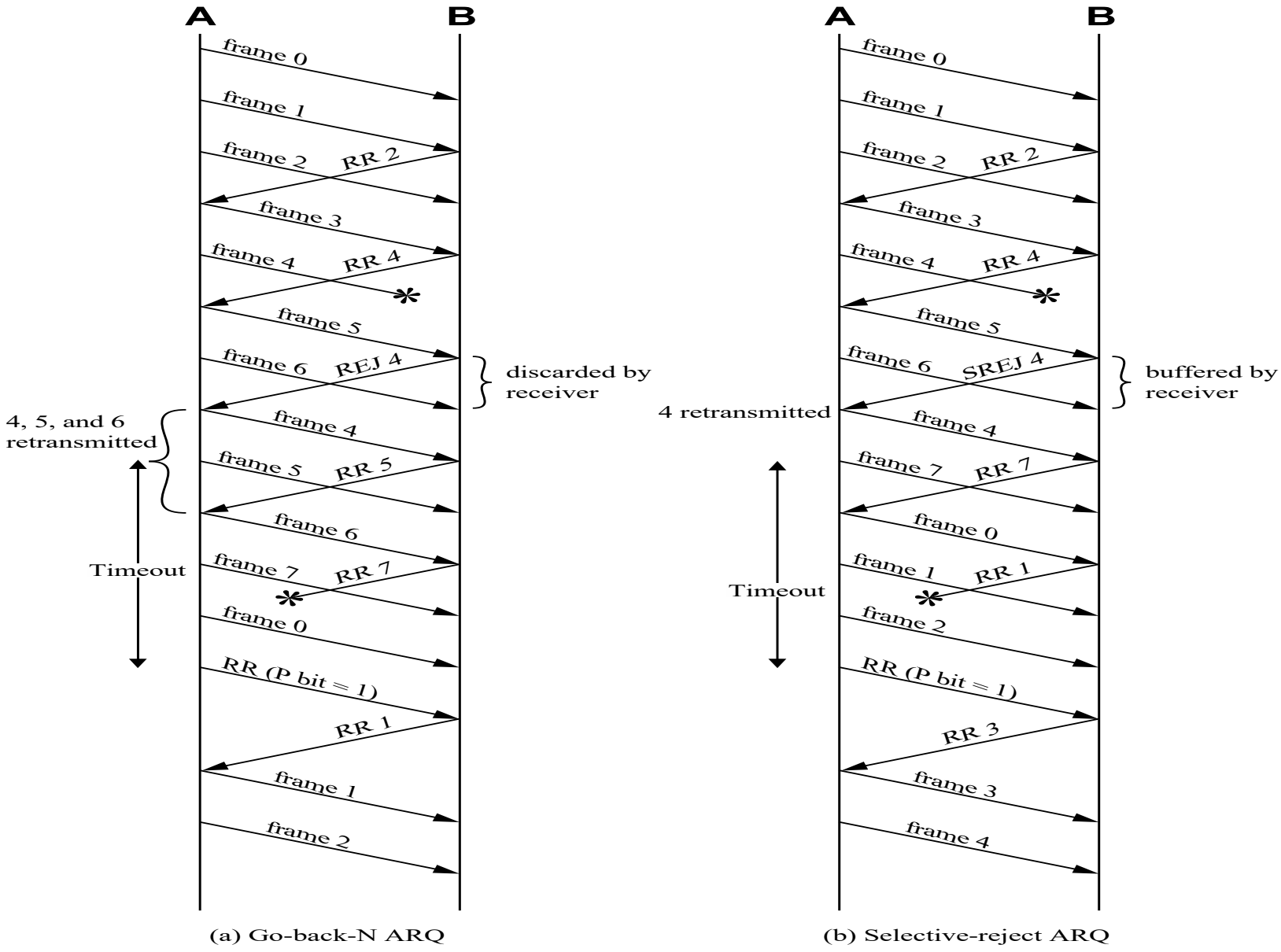


Figure 7.6 Sliding-Window ARQ Protocols

Logical Link Control (LLC)

- Transmission of link level PDUs between stations
- Must support multi-access, shared medium
- Relieved of some details of link access by the MAC layer
- Addressing involves specifying source and destination LLC users
  - Referred to as service access points (SAPs)
- Used in Access networks

Ref: Stallings Cap. 11.2

LLC Services

Unacknowledged connectionless service

- Data-gram style service
- Delivery of data is not guaranteed

Connection-mode service

- Logical connection is set up between two users
- Flow and error control are provided

Acknowledged connectionless service

- Datagrams are to be acknowledged, but no logical connection is set up

Ref: Stallings Cap. 11.2

LLC in MAC Protocol

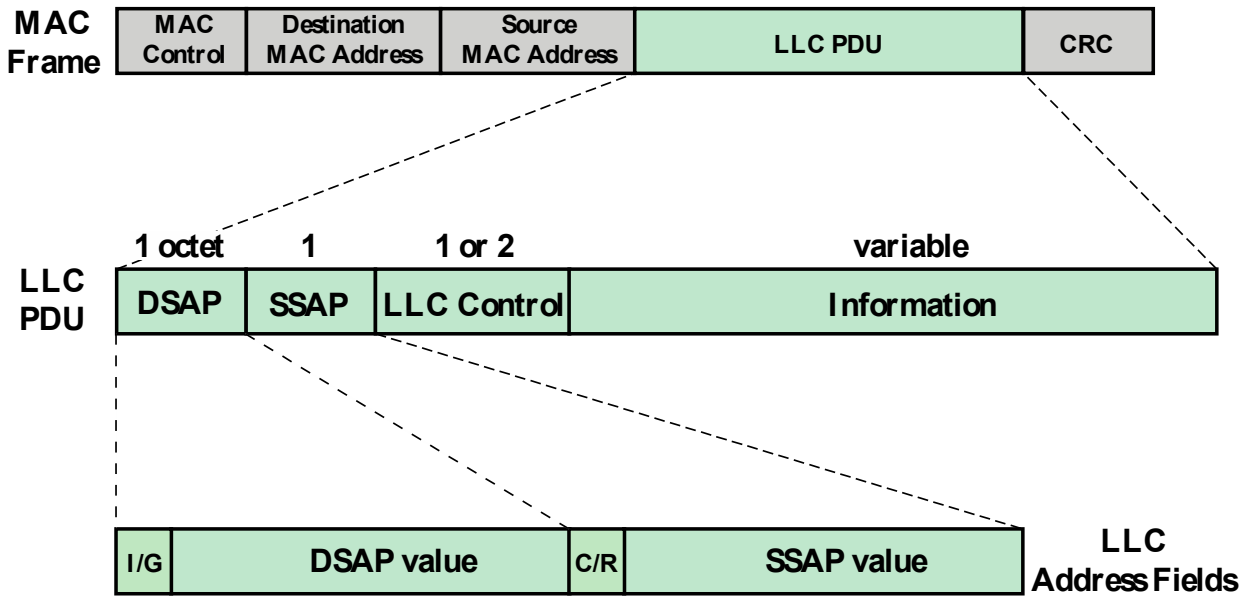


Figure 11.5 LLC PDU in a Generic MAC Frame Format

Ref: Stallings Cap. 11.2

LLC Control

- LLC takes advantage of the control field of the HDLC protocol
- Use of poll/final (P/F) bit depends on context
- In command frames P bit is set to 1 to solicit (poll) a response from the peer LLC entity
- In response frames F bit is set to 1 to indicate the response frame transmitted as a result of a soliciting command
- The basic control field for S- and I-frames uses 3 bit sequence numbers
  - An extended control field can be used that employs 7-bit sequence numbers
- U-frames always contain an 8-bit control field

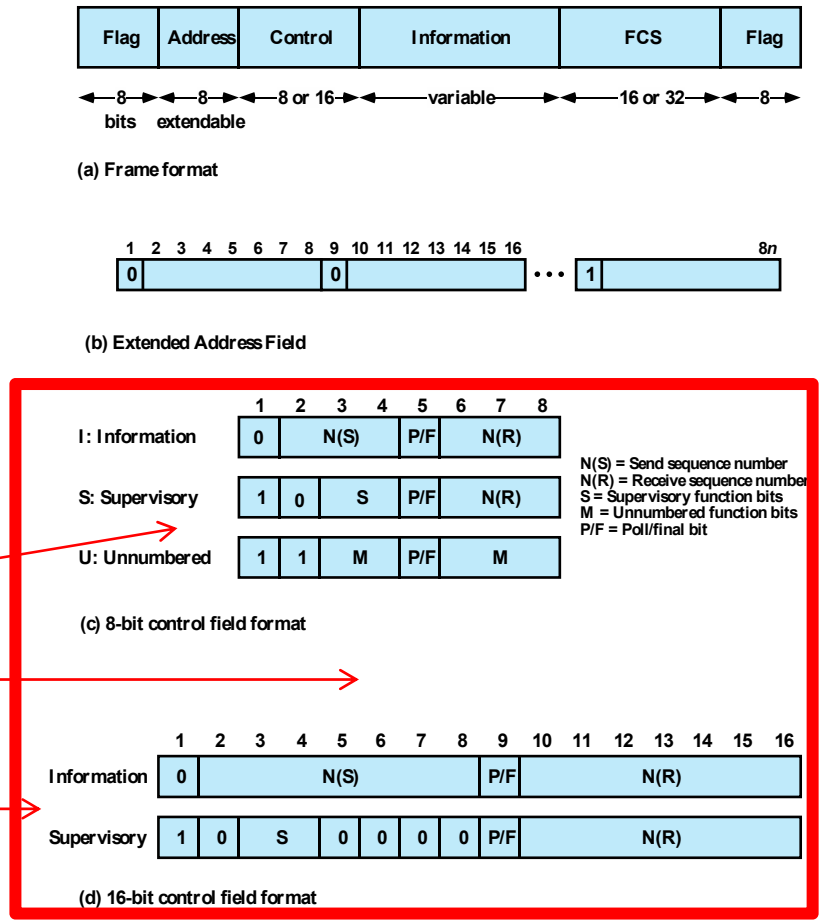


Figure 7.7 HDLC Frame Structure

Commands and Responses

Name	Command/ Response	Description
Information (I)	C/R	Exchange user data
Supervisory (S)		
Receive ready (RR)	C/R	Positive acknowledgment; ready to receive I-frame
Receive not ready (RNR)	C/R	Positive acknowledgment; not ready to receive
Reject (REJ)	C/R	Negative acknowledgment; go back N
Selective reject (SREJ)	C/R	Negative acknowledgment; selective reject
Unnumbered (U)		
Set normal response/extended mode (SNRM/SNRME)	C	Set mode; extended = 7-bit sequence numbers
Set asynchronous response/extended mode (SARM/SARME)	C	Set mode; extended = 7-bit sequence numbers
Set asynchronous balanced/extended mode (SABM, SABME)	C	Set mode; extended = 7-bit sequence numbers
Set initialization mode (SIM)	C	Initialize link control functions in addressed station
Disconnect (DISC)	C	Terminate logical link connection
Unnumbered Acknowledgment (UA)	R	Acknowledge acceptance of one of the set-mode commands
Disconnected mode (DM)	R	Responder is in disconnected mode
Request disconnect (RD)	R	Request for DISC command
Request initialization mode (RIM)	R	Initialization needed; request for SIM command
Unnumbered information (UI)	C/R	Used to exchange control information
Unnumbered poll (UP)	C	Used to solicit control information
Reset (RSET)	C	Used for recovery; resets N(R), N(S)
Exchange identification (XID)	C/R	Used to request/report status
Test (TEST)	C/R	Exchange identical information fields for testing
Frame reject (FRMR)	R	Report receipt of unacceptable frame

(Table can be found on page 230 in the textbook)

Exemples

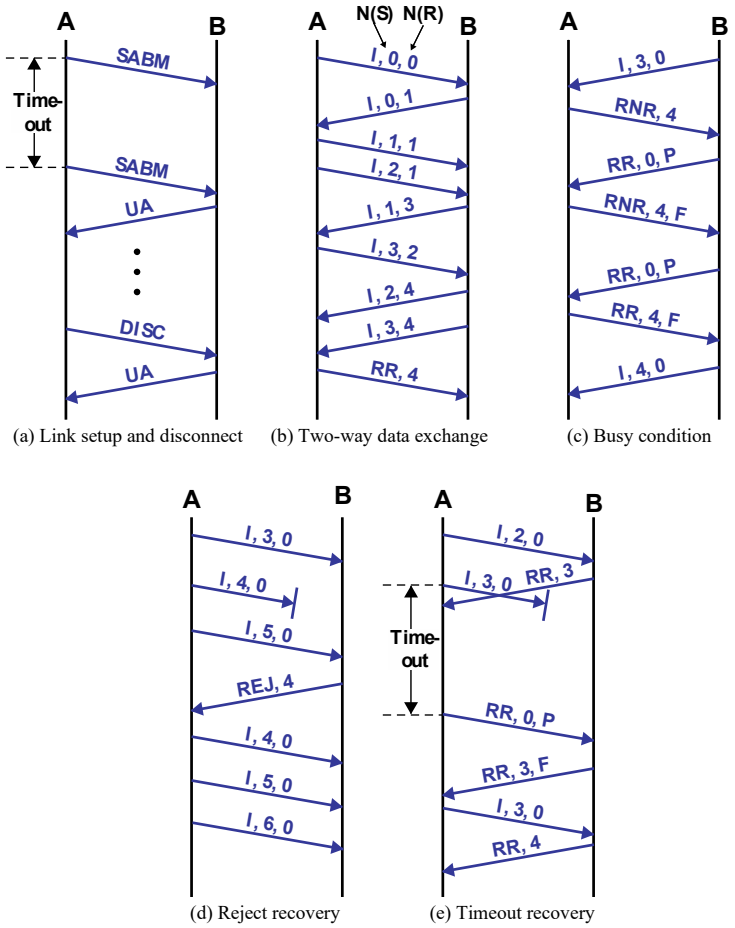


Figure 7.9 Examples of HDLC Operation

Ethernet MAC Frame format.

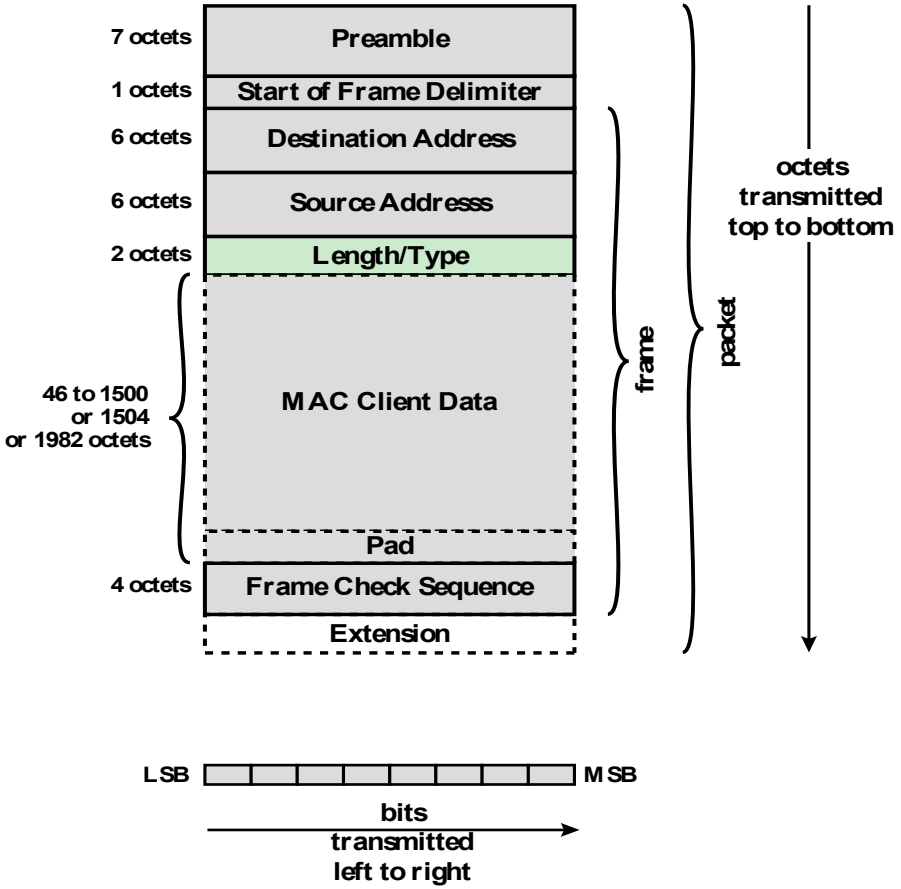


Figure 12.4 IEEE 802.3 MAC Frame Format

Gigabit Ethernet Medium Options

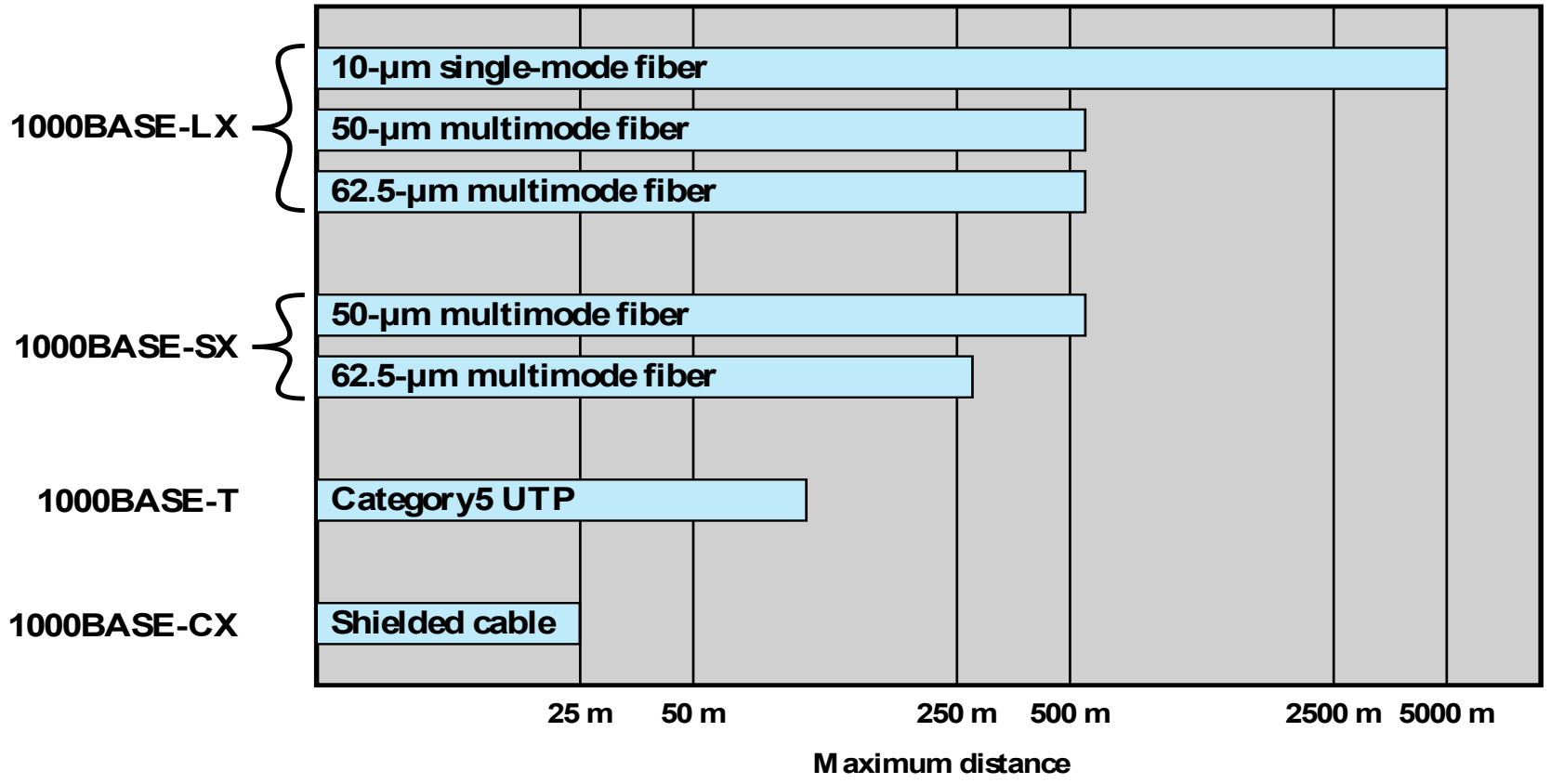


Figure 12.5 Gigabit Ethernet Medium Options (log scale)

10 Gbps Ethernet Distance Options

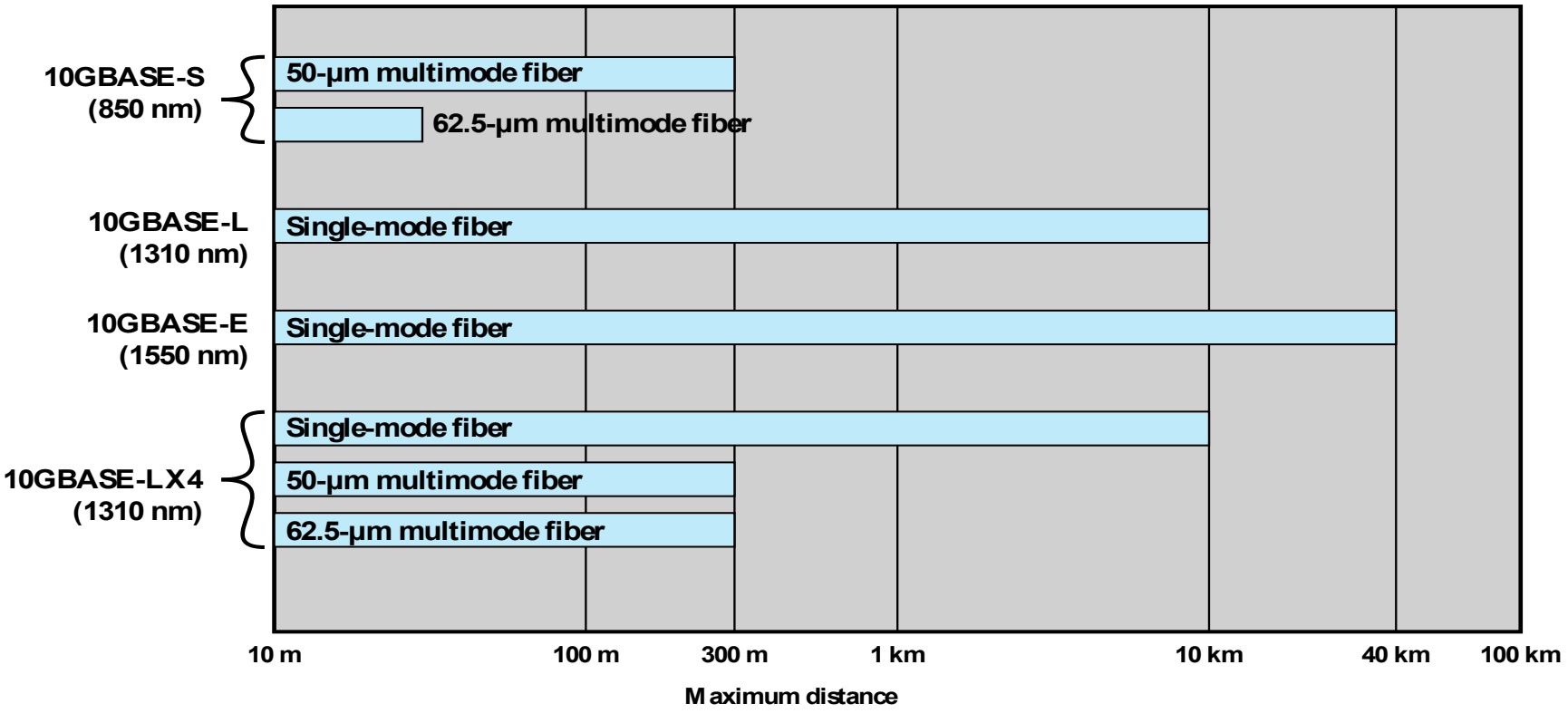


Figure 12.7 10-Gbps Ethernet Distance Options (log scale)

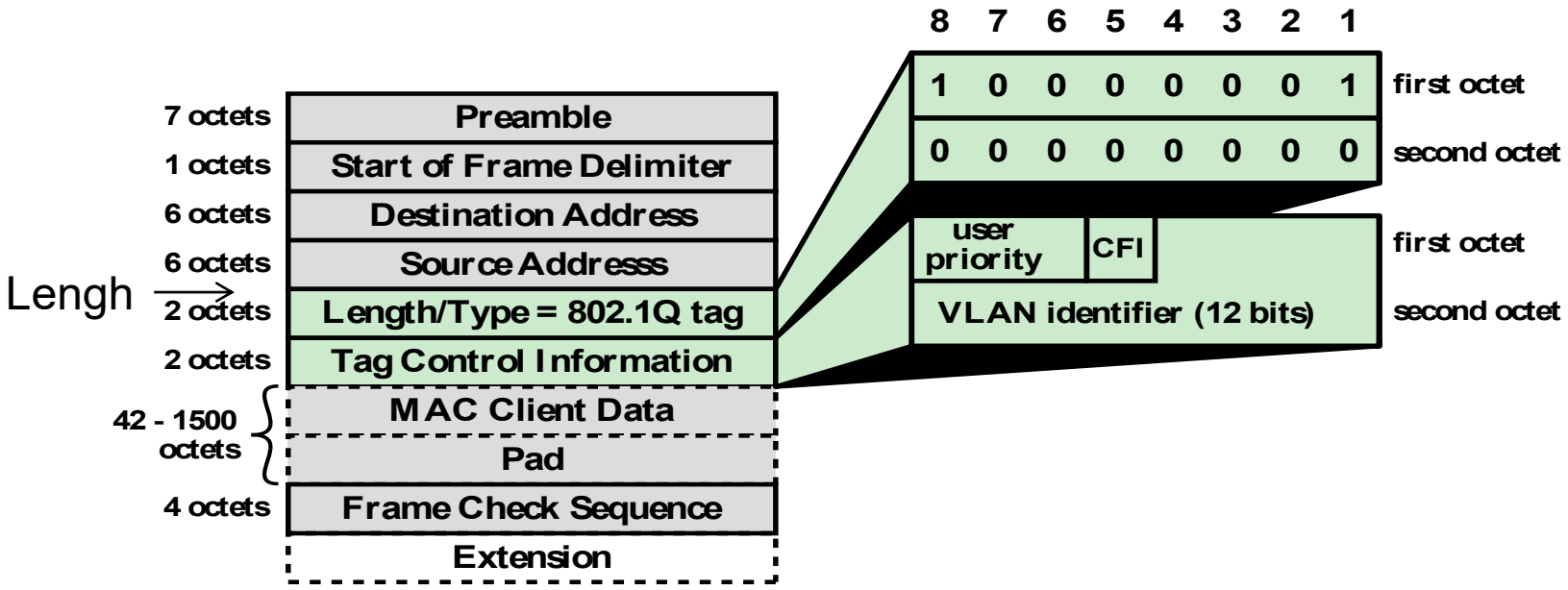
Media Options for 40-Gbps and 100-Gbps Ethernet

	40 Gbps	100 Gbps
1m backplane	40GBASE-KR4	
10 m copper	40GBASE-CR4	1000GBASE-CR10
100 m multimode fiber	40GBASE-SR4	1000GBASE-SR10
10 km single mode fiber	40GBASE-LR4	1000GBASE-LR4
40 km single mode fiber		1000GBASE-ER4

Naming nomenclature:

Copper: K = backplane; C = cable assembly
Optical: S = short reach (100m); L - long reach (10 km); E = extended long reach (40 km)
Coding scheme: R = 64B/66B block coding
Final number: number of lanes (copper wires or fiber wavelengths)

Tagged IEEE 802.3 MAC Frame Format

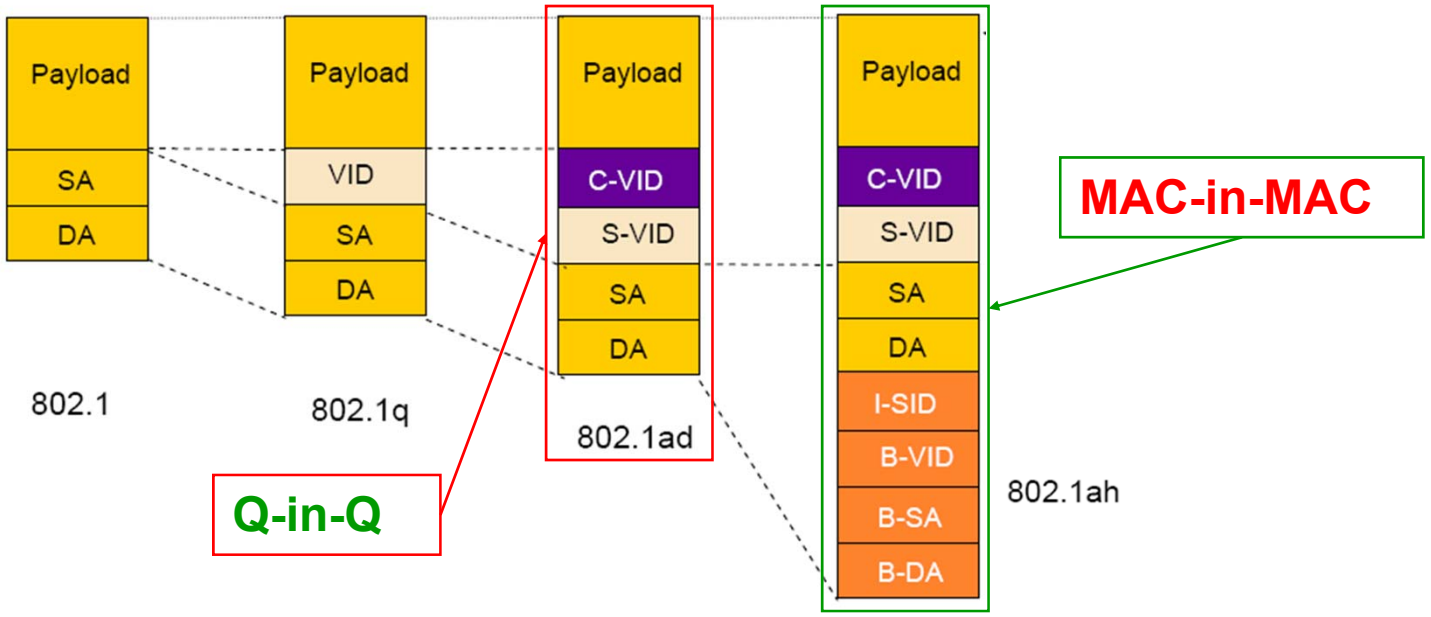


CFI = Canonical Format Indicator
VLAN = virtual local area network

Figure 12.10 Tagged IEEE 802.3 MAC Frame Format

Provider Backbone Bridge Traffic Engineering (PBB-TE)

- **IEEE has developed a number of standards providing enhancements to the original Ethernet standards. PBB-TE adapts Ethernet technology to carrier class transport networks**
  - **802.1Q**: Virtual LAN
  - **802.1ad**: Provider Bridging
  - **802.1ah**: Provider Backbone Bridging
  - **802.1ag**: Connectivity Fault Management (OAM)



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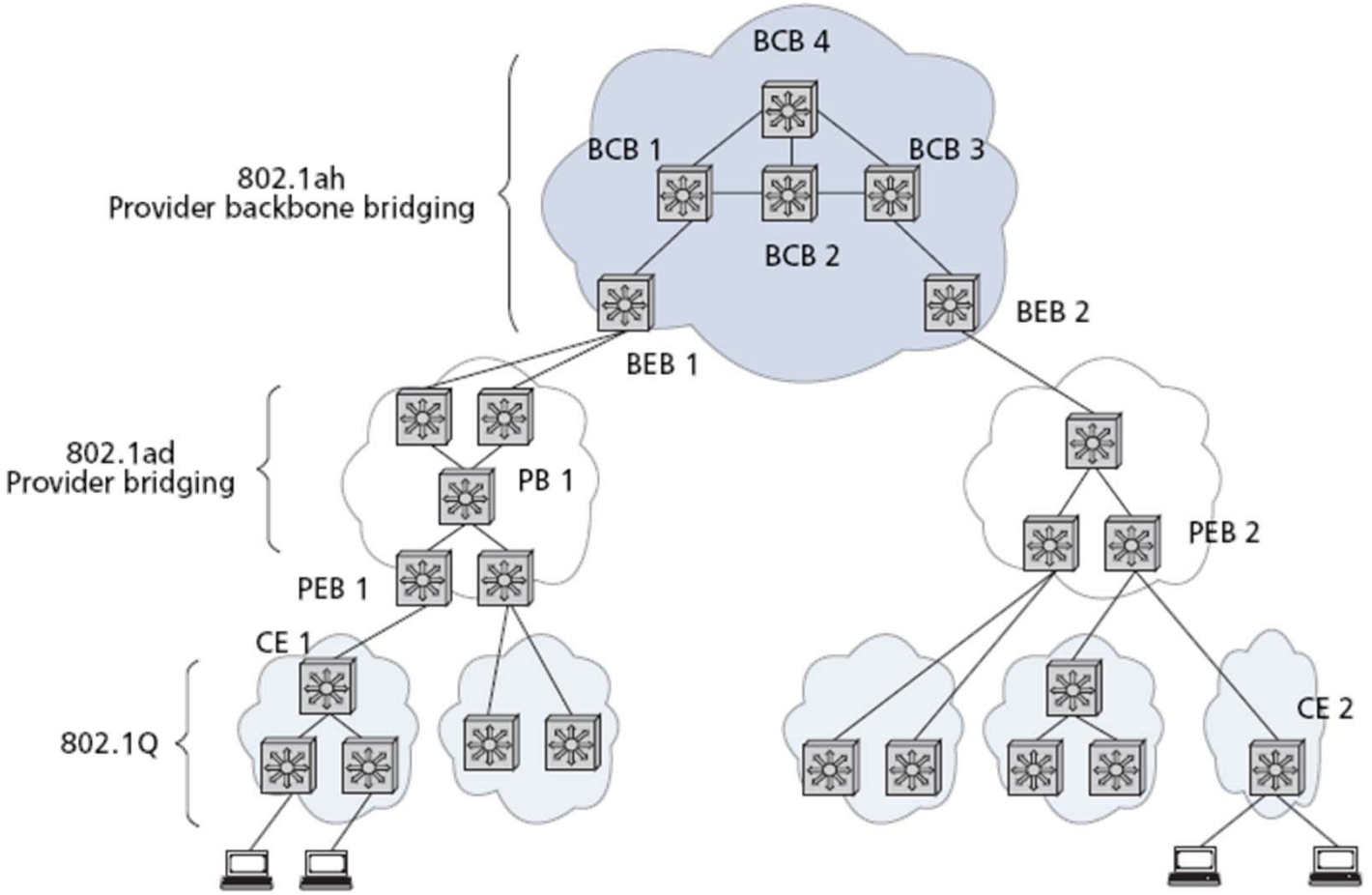
The way to PBB-TE



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3.2 Control de la congestió i QoS

Queues at Node

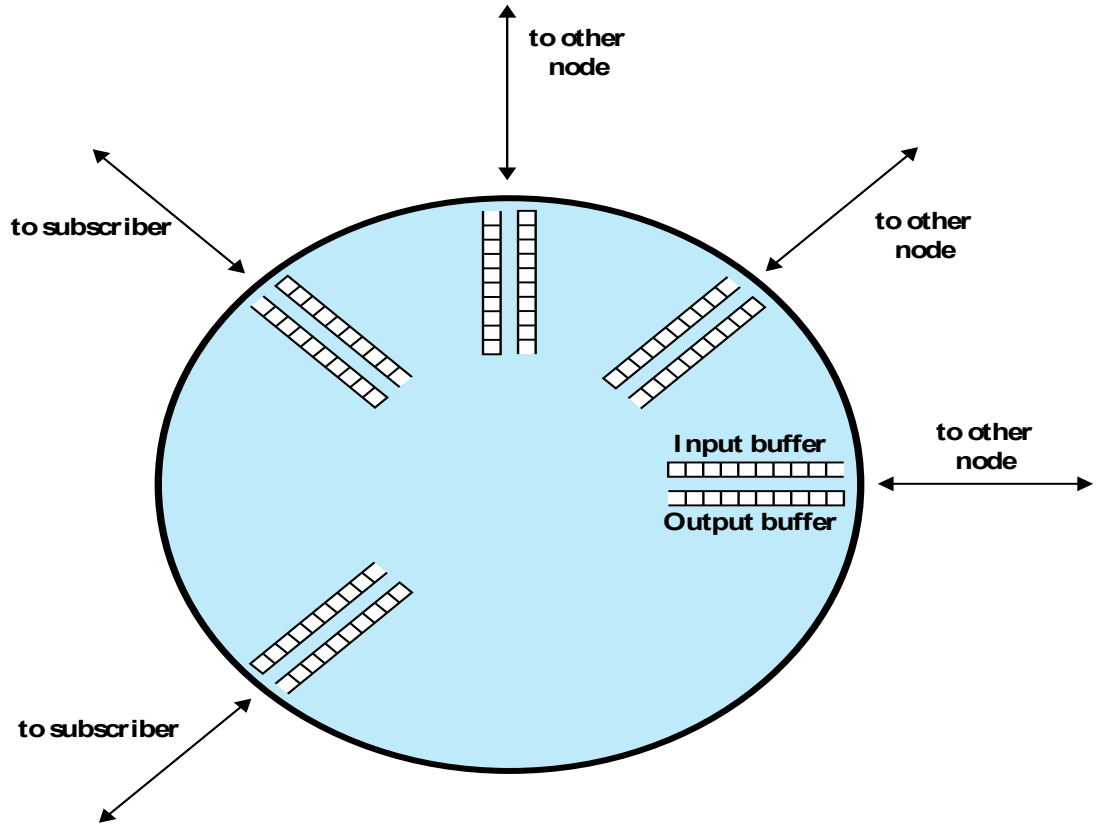


Figure 20.1 Input and Output Queues at Node

Interaction of Queues in a data network

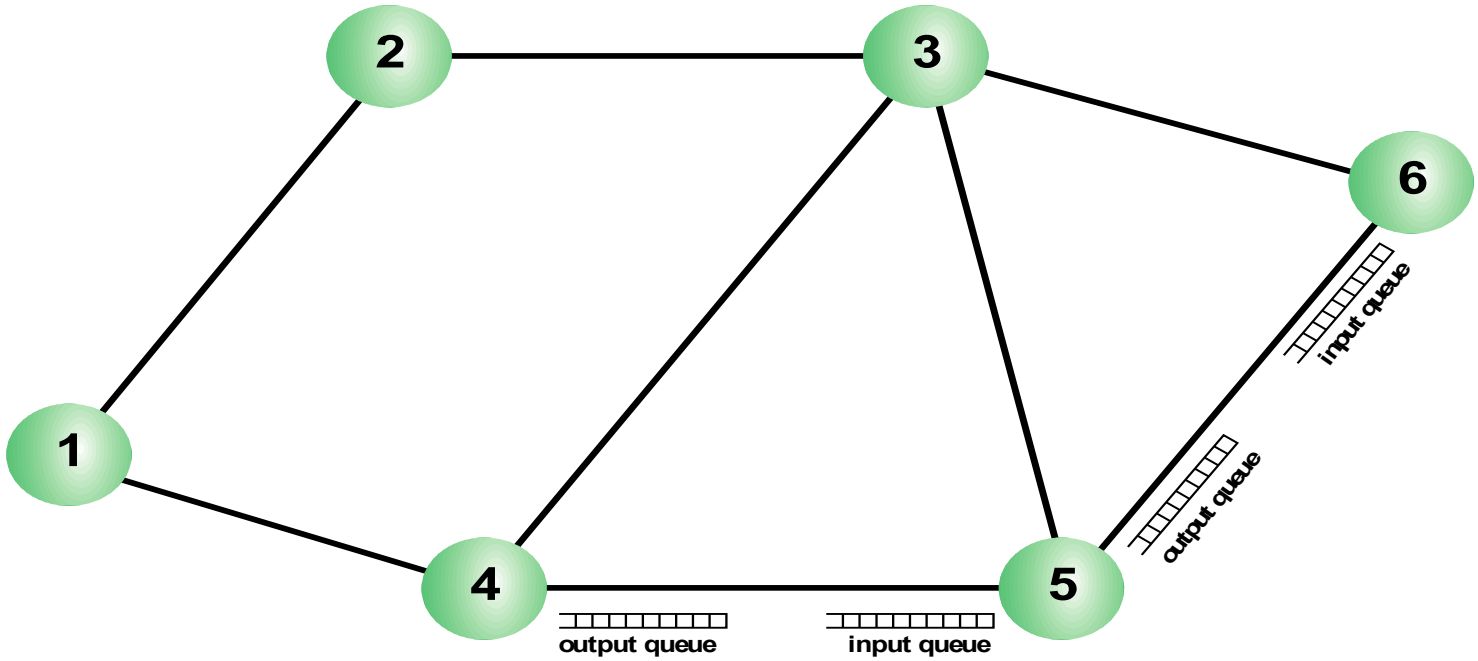
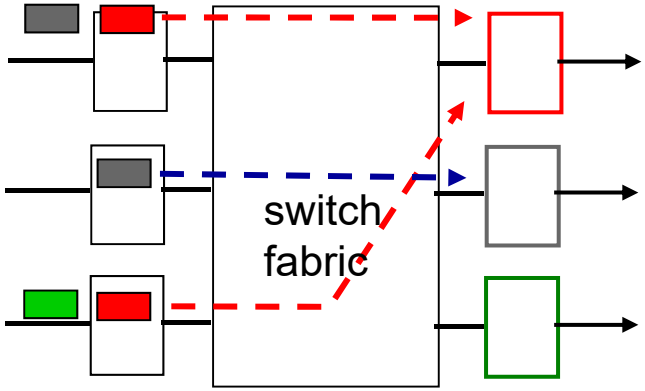


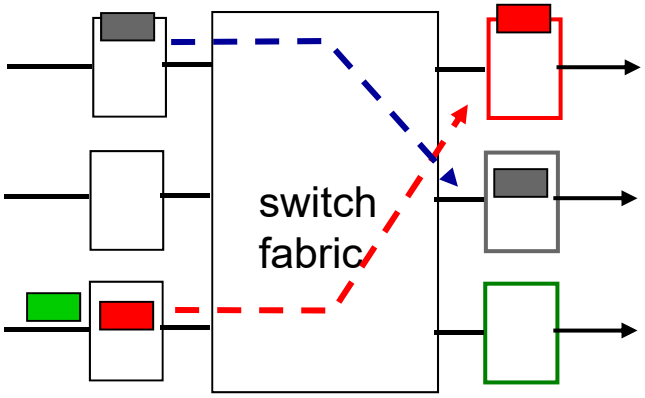
Figure 20.2 Interaction of Queues in a Data Network

Input port queuing

- fabric slower than input ports combined -> queueing may occur at input queues
  - *queueing delay and loss due to input buffer overflow!*
- Head-of-the-Line (HOL) blocking: queued datagram at front of queue prevents others in queue from moving forward

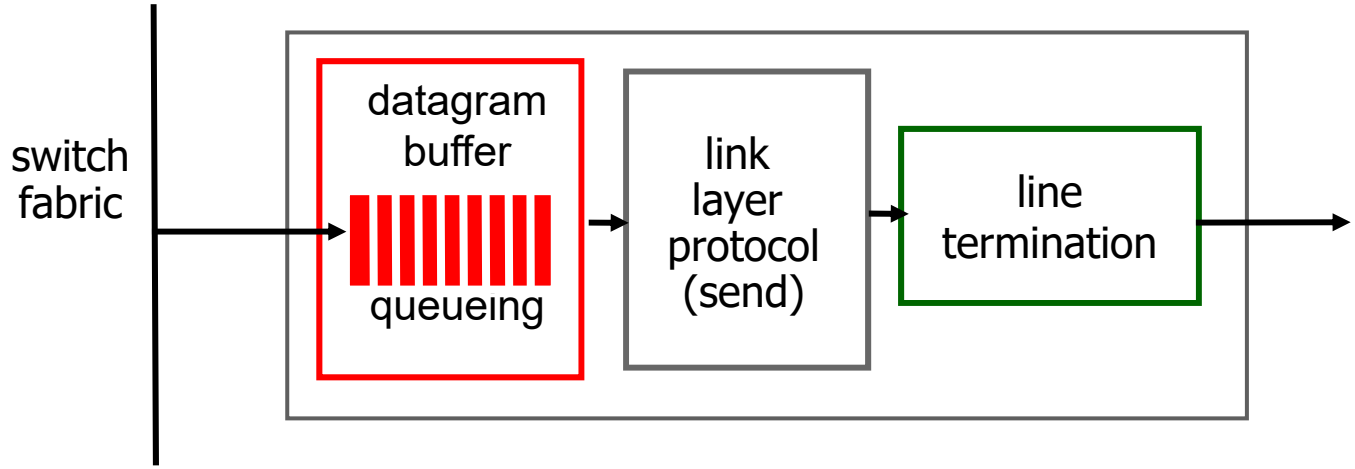


output port contention:
only one red datagram can be transferred.
lower red packet is blocked



one packet time later:
green packet
experiences HOL
blocking

Output ports



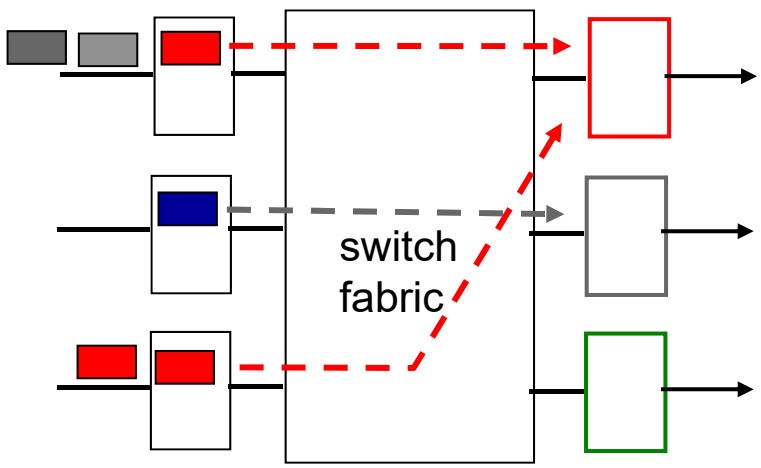
- *buffering* required when datagrams arrive from fabric faster than the transmission rate

Datagram (packets) can be lost due to congestion, lack of buffers

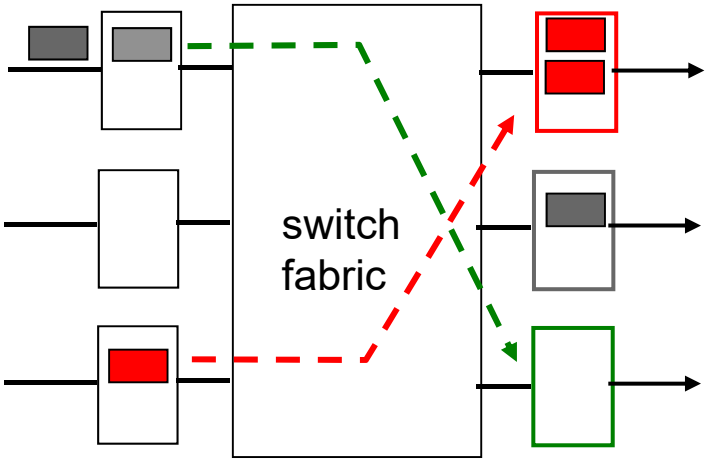
- *scheduling discipline* chooses among queued datagrams for transmission

Priority scheduling – who gets best performance, network neutrality

Output port queueing



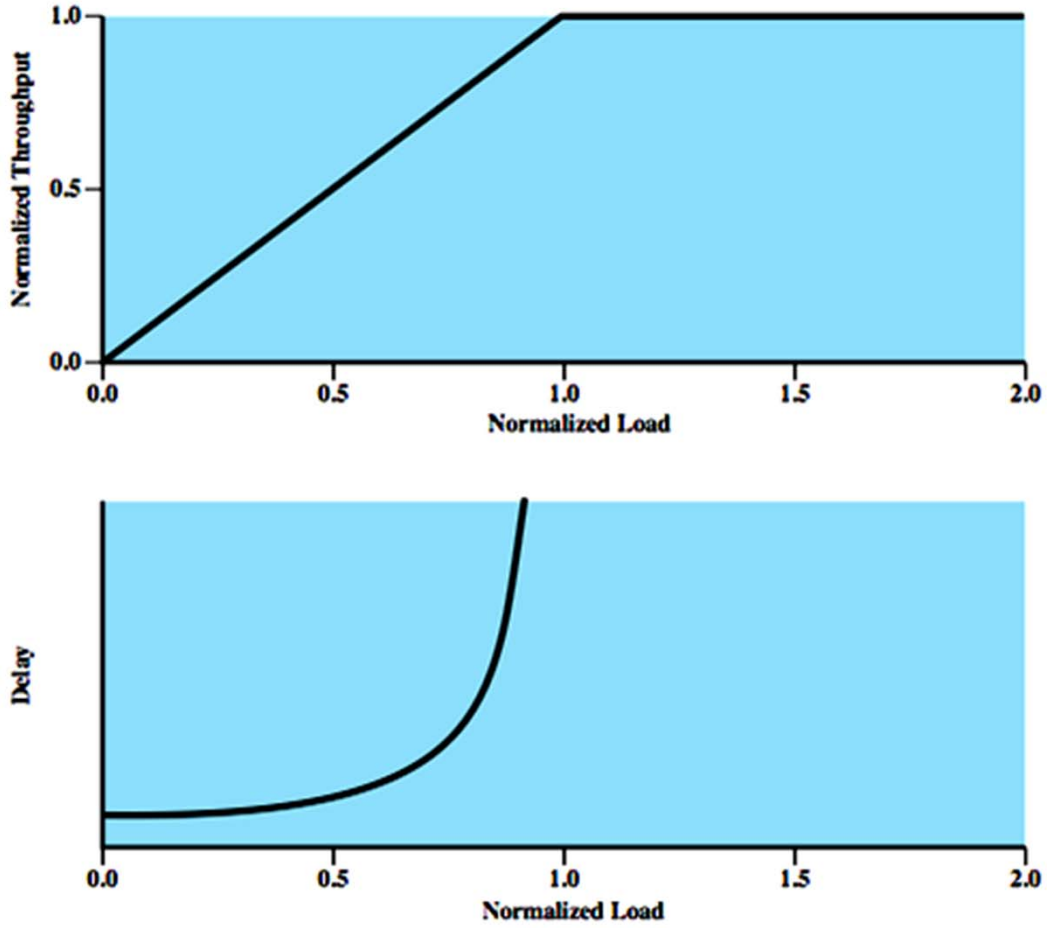
at *t*, packets more from input to output



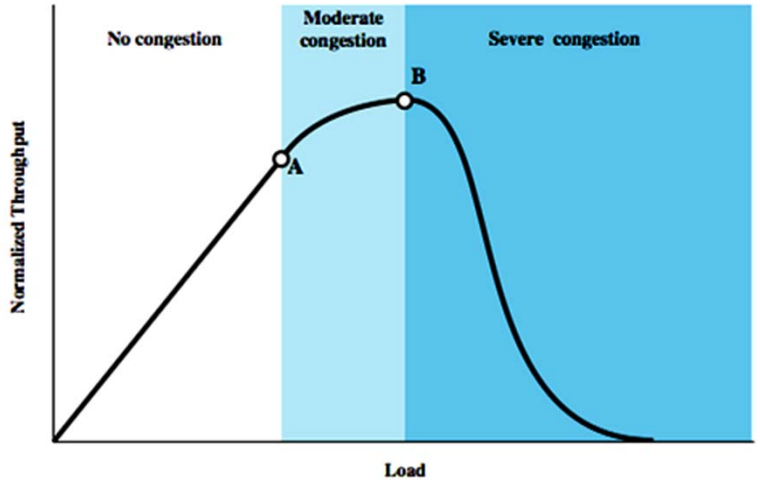
one packet time later

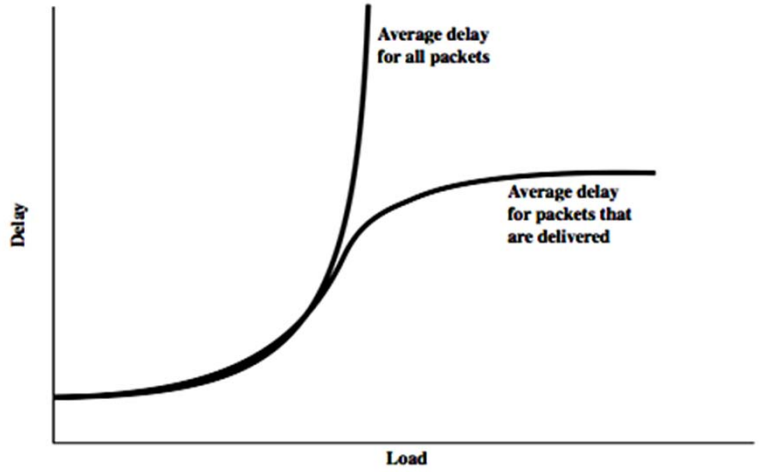
- buffering when arrival rate via switch exceeds output line speed
- *queueing (delay) and loss due to output port buffer overflow!*

Ideal Network Utilization

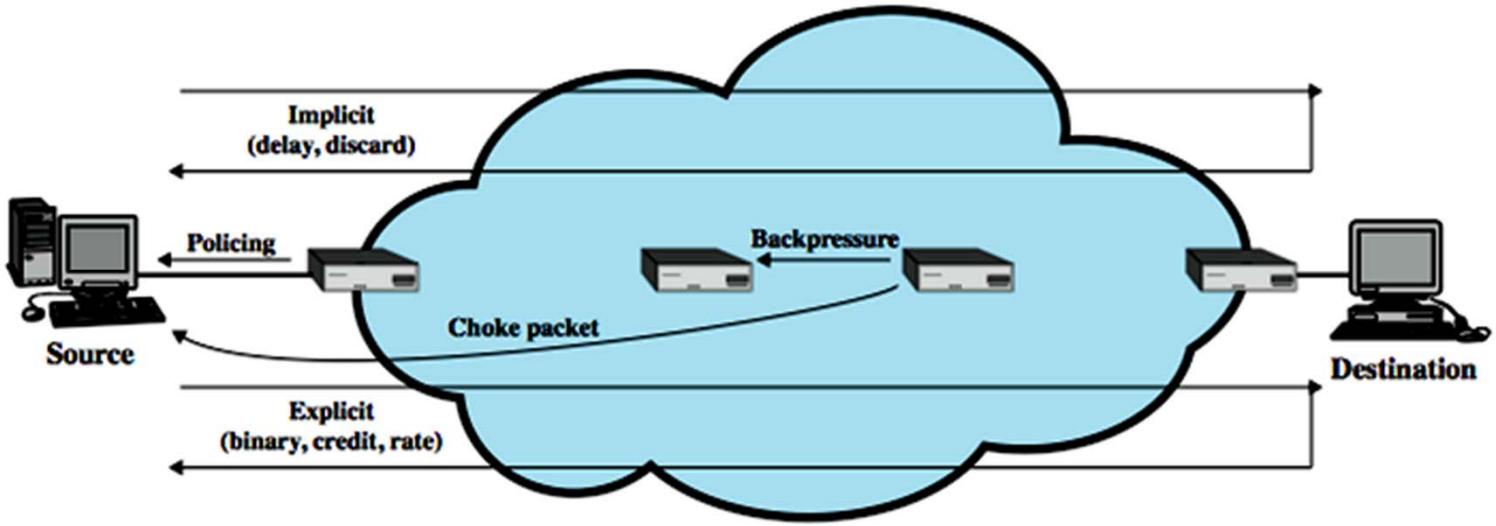


Effects of Congestion - No Control





Mechanisms for Congestion Control



Traffic Management

Fairness

- Provide equal treatment of various flows

Quality of service

- Different treatment for different connections

Reservations

- Traffic contract between user and network
- Excess traffic discarded or handled on a best-effort basis

Type of applications

- Interactive communications
  - Audio/video conferencing
- Information retrieval
  - Download of audio/video streams
- File transfer (data retrieval)
  - Access to databases and/or repositories
  - e-mail

Phenomena impacting in these applications

- Lost of data
- End-to-end delay
- Delay jitter
- Throughput (Bandwidth)
- Network failures

What is QoS?

- QoS is usually expressed as the combination of network-imposed features such as delay, delay jitter, bandwidth (throughput), packet loss, and reliability affecting the quality of the transmission
- Basically, there are two categories of QoS parameters
  - Technology based
    - *System parameters*
  - User Perception based,
    - *Also known as Quality of Experience (QoE)*

QoS Parameters

- Required QoS can be defined by several parameters
  - **Delay:** how long it takes for a packet to traverse the network?
  - **Jitter:** what is the variance in the delay?
  - **Loss:** how often packets get lost in the network and never show up at the destination?
- Are the value of these parameters affordable?

Service Categories

Real time - limit amount/variation of delay

- Constant bit rate (CBR)
- Real time variable bit rate (rt-VBR)

Non-real time - for bursty traffic

- Non-real time variable bit rate (nrt-VBR)
- Unspecified bit rate (UBR)

Traffic Shaping/Traffic Policing

- Two important tools in network management:
  - Traffic shaping
    - *Concerned with traffic leaving the switch*
    - *Reduces packet clumping*
    - *Produces an output packet stream that is less burst and with a more regular flow of packets*
  - Traffic policing
    - *Concerned with traffic entering the switch*
    - *Packets that don't conform may be treated in one of the following ways:*
      - *Give the packet lower priority compared to packets in other output queues*
      - *Label the packet as nonconforming by setting the appropriate bits in a header*
      - *Discard the packet*

Token Bucket / Leaky Bucket

- Widely used traffic management tool
- Advantages:
  - Many traffic sources can be defined easily and accurately
  - Provides a concise description of the load to be imposed by a flow, enabling the service to determine easily the resource requirement
  - Provides the input parameters to a policing function

Token bucket

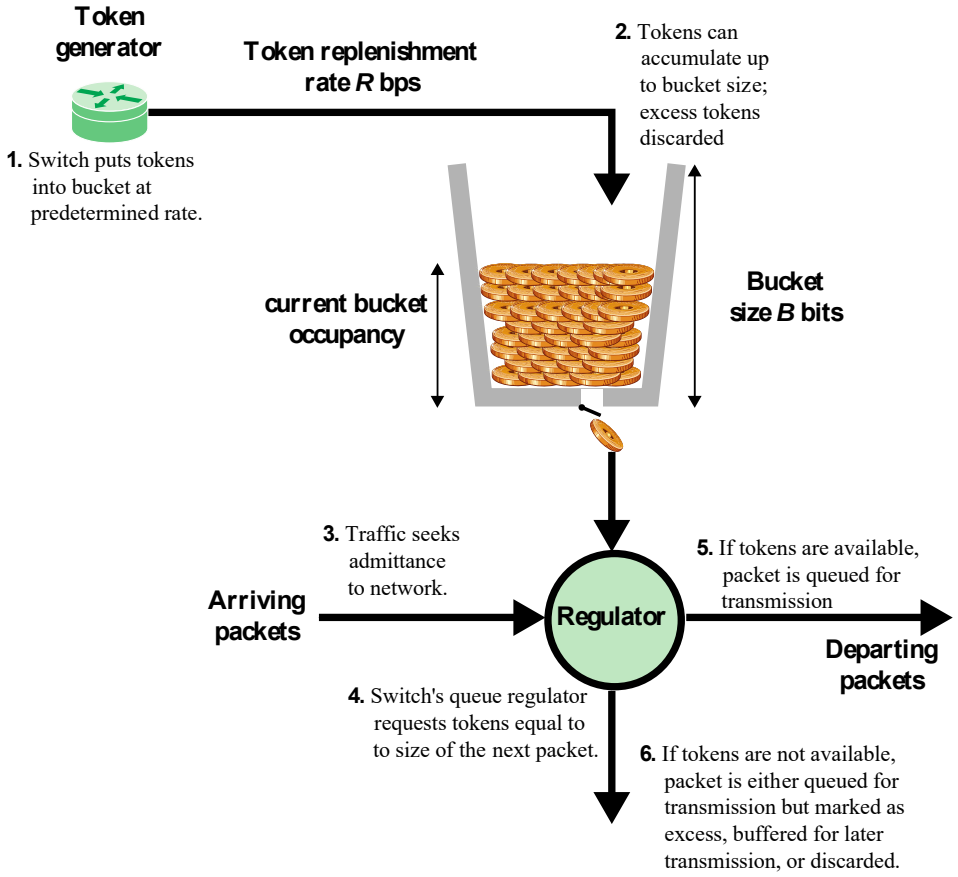


Figure 20.6 Token Bucket Scheme

Leaky bucket

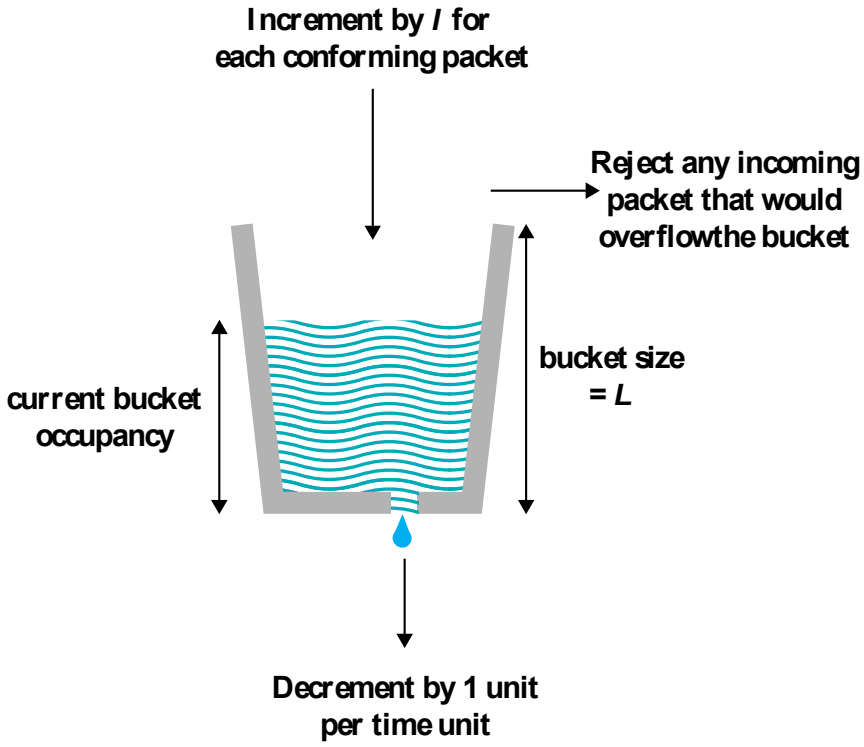
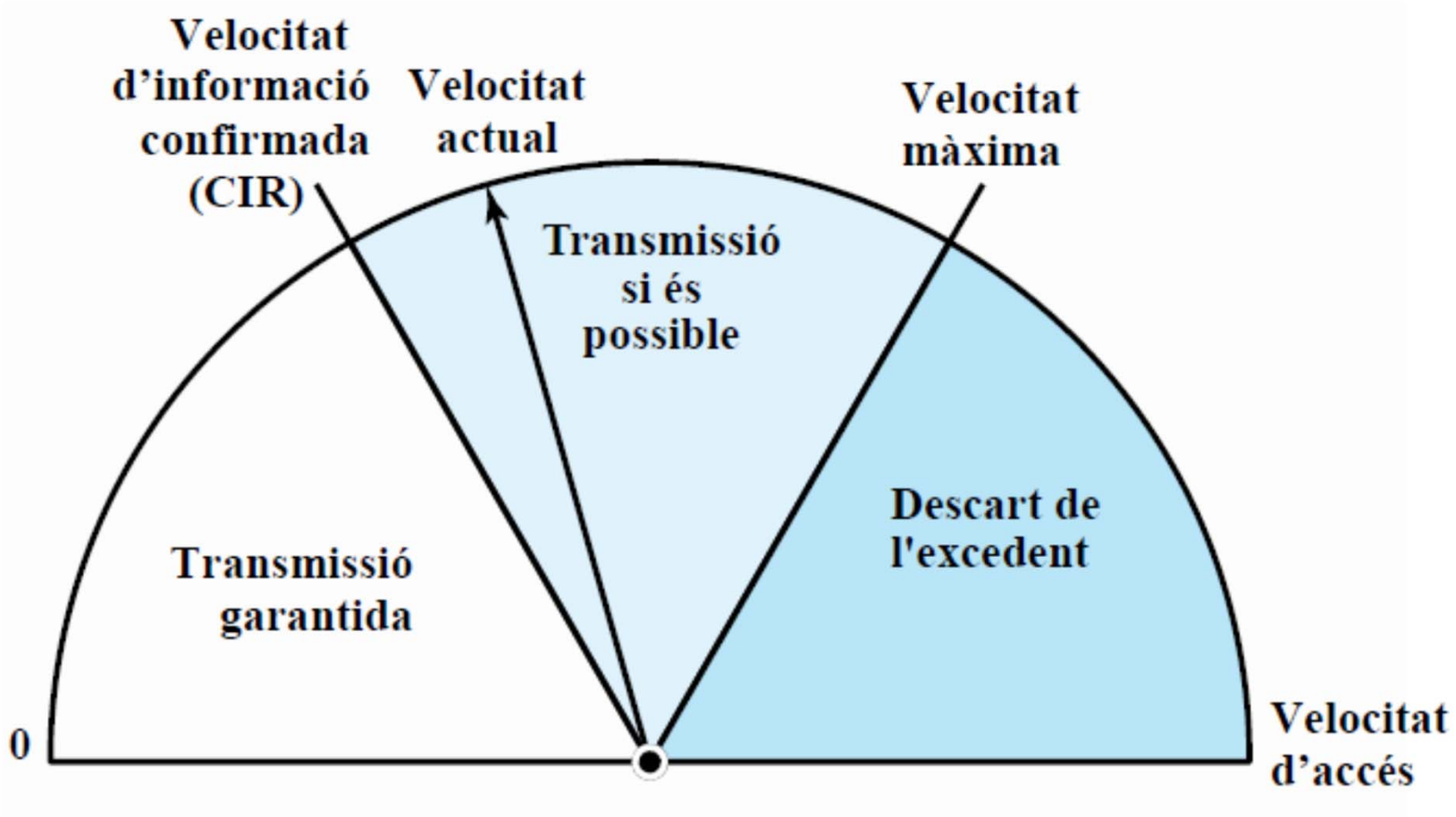
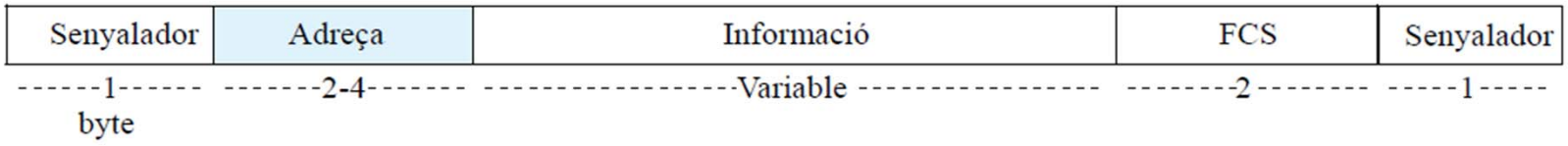


Figure 20.7 Leaky Bucket Algorithm

CIR strategy



Level 2. FR: Frame Relay: LAPF Core



(a) Format de trama

8	7	6	5	4	3	2	1
DLCI superior						C/R	EA 0
DLCI inferior				FECN	BECN	DE	EA 1

(b) Camp d'adreça: 2 bytes (per defecte)

8	7	6	5	4	3	2	1
DLCI superior						C/R	EA 0
DLCI				FECN	BECN	DE	EA 0
DLCI							EA 0
Control DLCI inferior o DL-CORE						D/C	EA 1

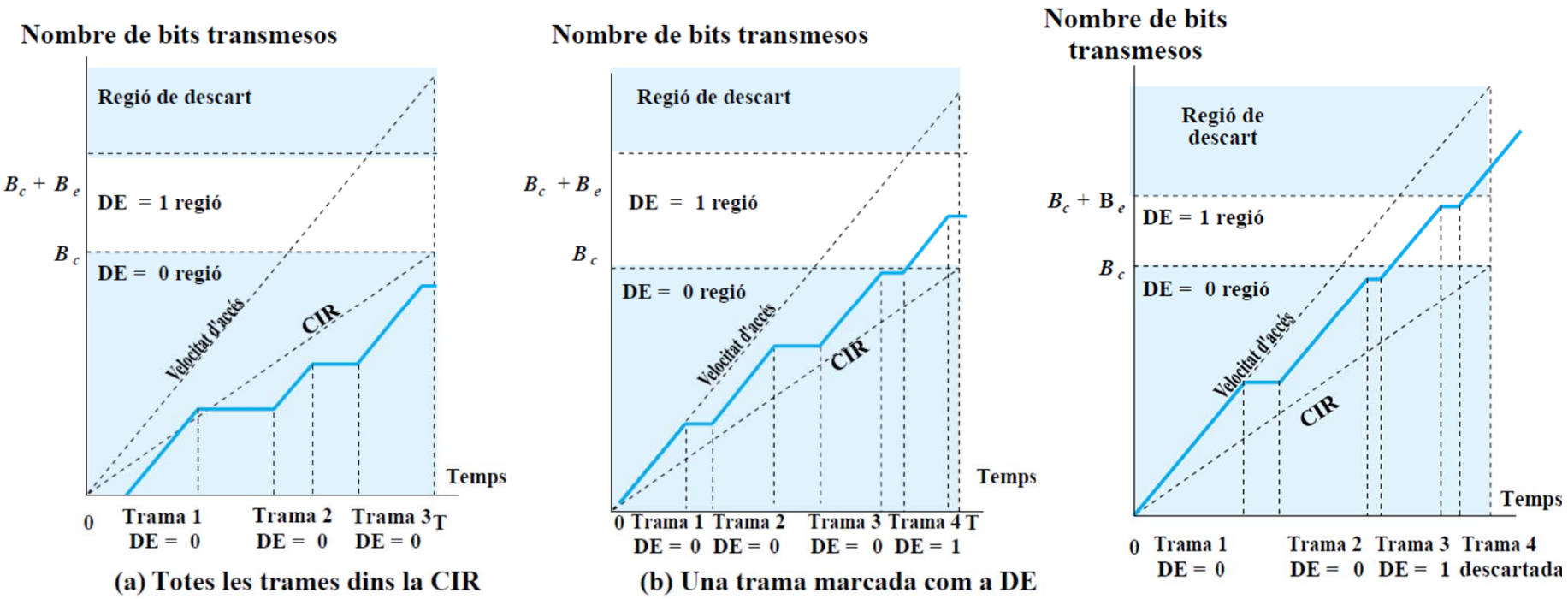
(d) Camp d'adreça: 4 bytes

8	7	6	5	4	3	2	1
DLCI superior						C/R	EA 0
DLCI				FECN	BECN	DE	EA 0
Control DLCI inferior o DL-CORE						D/C	EA 1

(c) Camp d'adreça: 3 bytes

EA	Bit d'extensió de camp d'adreça
C/R	Bit d'ordre/resposta
FECN	Notificació de congestió explícita cap endavant
BECN	Notificació de congestió explícita cap enrere
DLCI	Identificador de connexió d'enllaç de dades
D/C	Indicador de control DLCI o DL-CORE
DE	Idoneïtat del descart

Exemple Congestion control



$$T = \frac{B_c}{CIR}$$

3.3 Commutació d'etiquetes MPLS

Network-layer functions

Recall: two network-layer functions:

- *forwarding:* move packets from router's input to appropriate router output — *data plane*
- *routing:* determine route taken by packets from source to destination — *control plane*

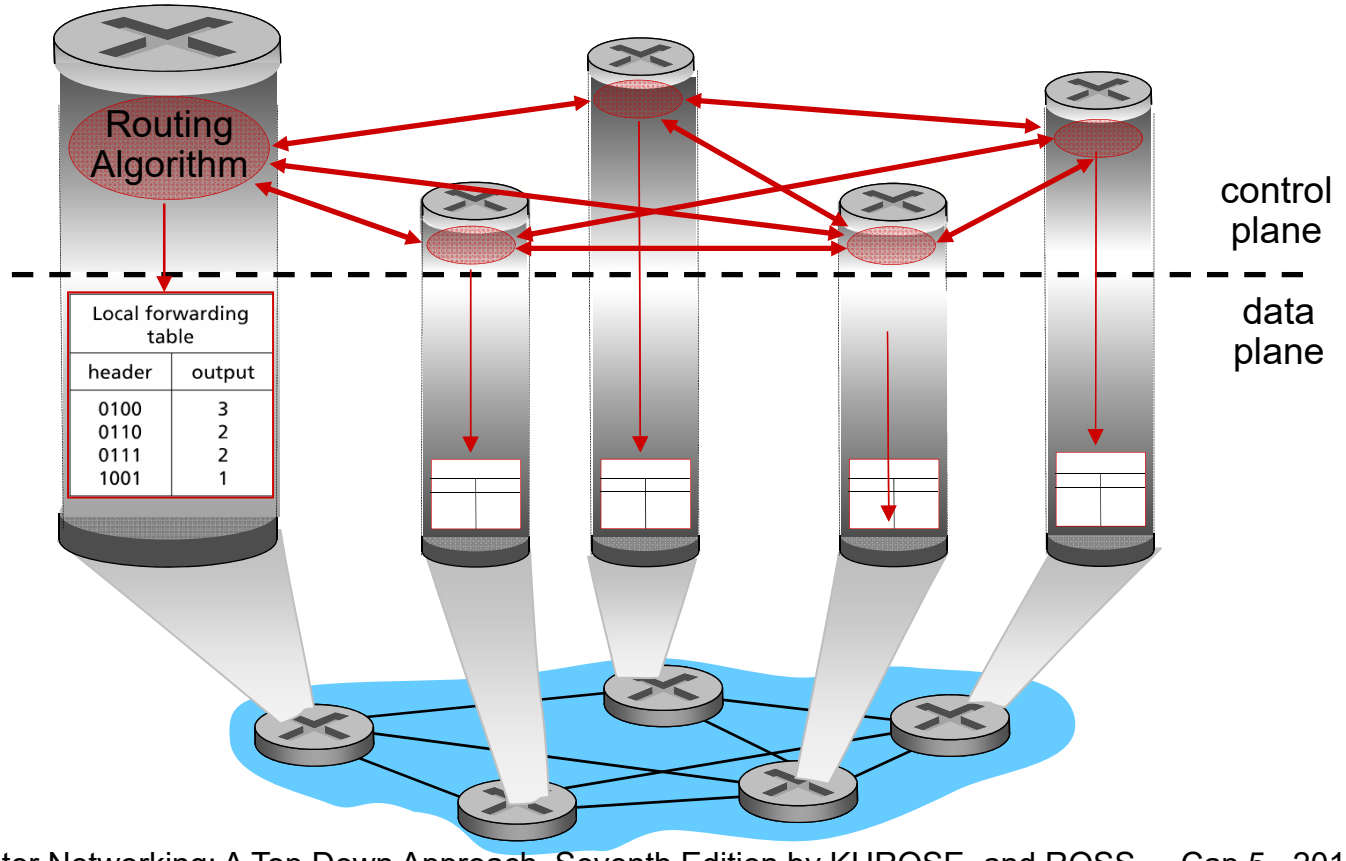
Two approaches to structuring network control plane:

- per-router control (traditional)
- logically centralized control (software defined networking)

Book: Computer Networking: A Top Down Approach, Seventh Edition by KUROSE and ROSS . , Cap 5 . 2017

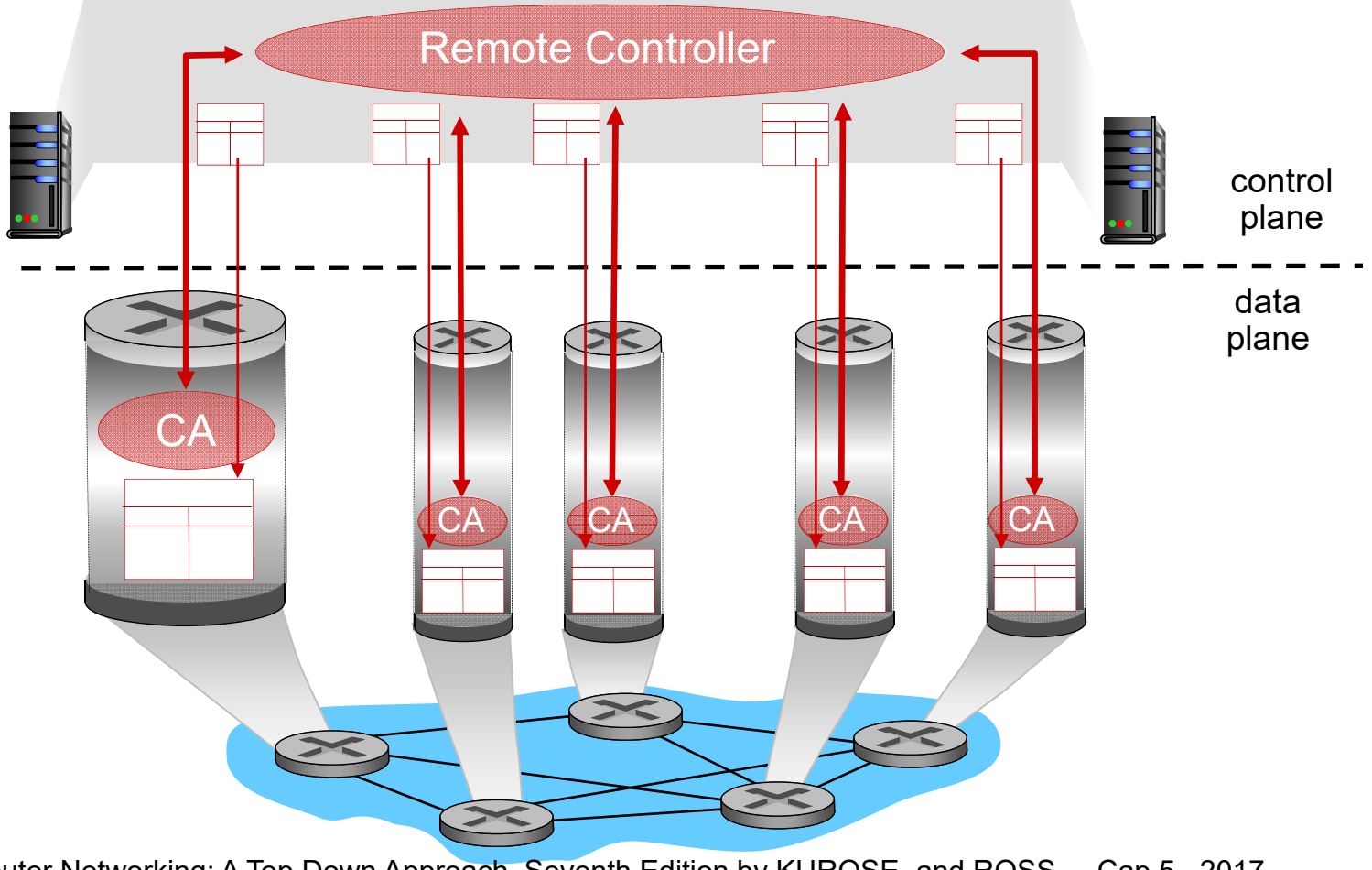
Per-router control plane

Individual routing algorithm components *in each and every router* interact with each other in control plane to compute forwarding tables



Logically centralized control plane

A distinct (typically remote) controller interacts with local control agents (CAs) in routers to compute forwarding tables



Book: Computer Networking: A Top Down Approach, Seventh Edition by KUROSE and ROSS . , Cap 5 . 2017

Role of MPLS

- Efficient technique for forwarding and routing packets
- Designed with IP networks in mind
  - *Can be used with any link-level protocol*
- Fixed-length label encapsulates an IP packet or a data link frame
- MPLS label contains all information needed to perform routing, delivery, QoS, and traffic management functions
- Is connection oriented

Traffic Engineering

- Ability to define routes dynamically, plan resource commitments on the basis of known demand, and optimize network utilization
- Effective use can substantially increase usable network capacity
- ATM provided strong traffic engineering capabilities prior to MPLS
- With basic IP there is a primitive form

MPLS
• **Is aware of flows with QoS requirements** • **Possible to set up routes on the basis of flows** • **Paths can be rerouted intelligently**

MPLS Operation

- Label switching routers (LSRs)
  - *Nodes capable of switching and routing packets on the basis of label*
- Labels define a flow of packets between two endpoints
- Assignment of a particular packet is done when the packet enters the network of MPLS routers
- Connection-oriented technology

MPLS Operation

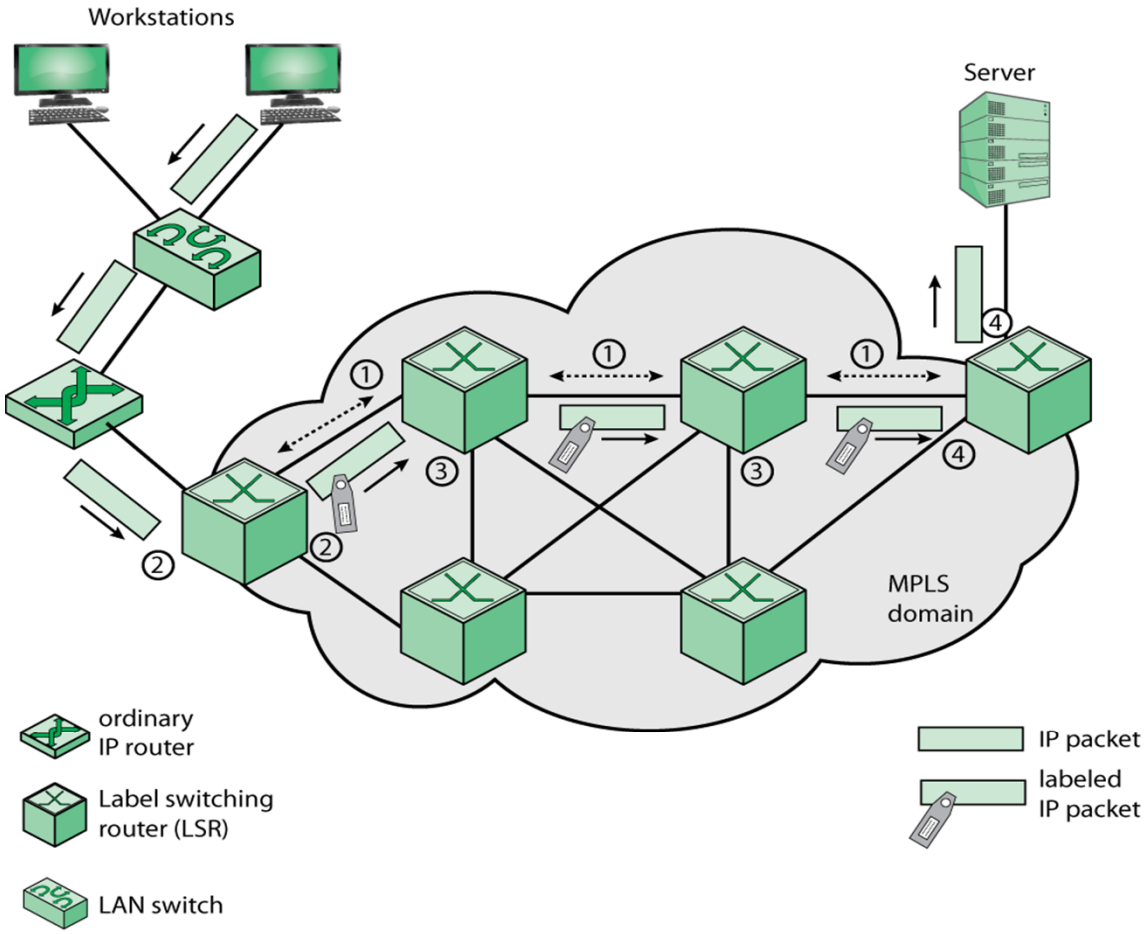


Figure 21.1 MPLS Operation

MPLS Packet Forwarding

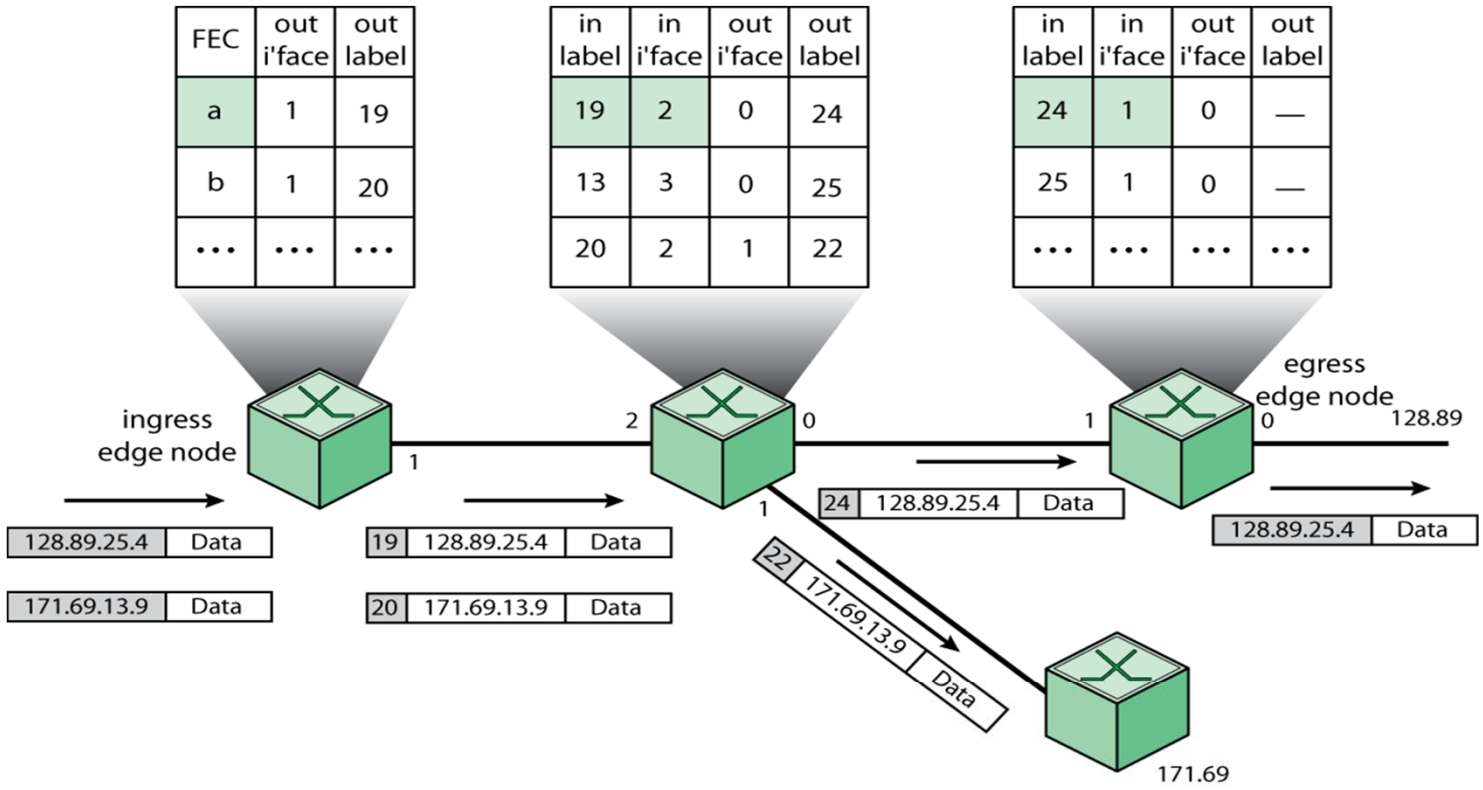


Figure 21.2 MPLS Packet Forwarding

LSP Creation and Packet Forwarding

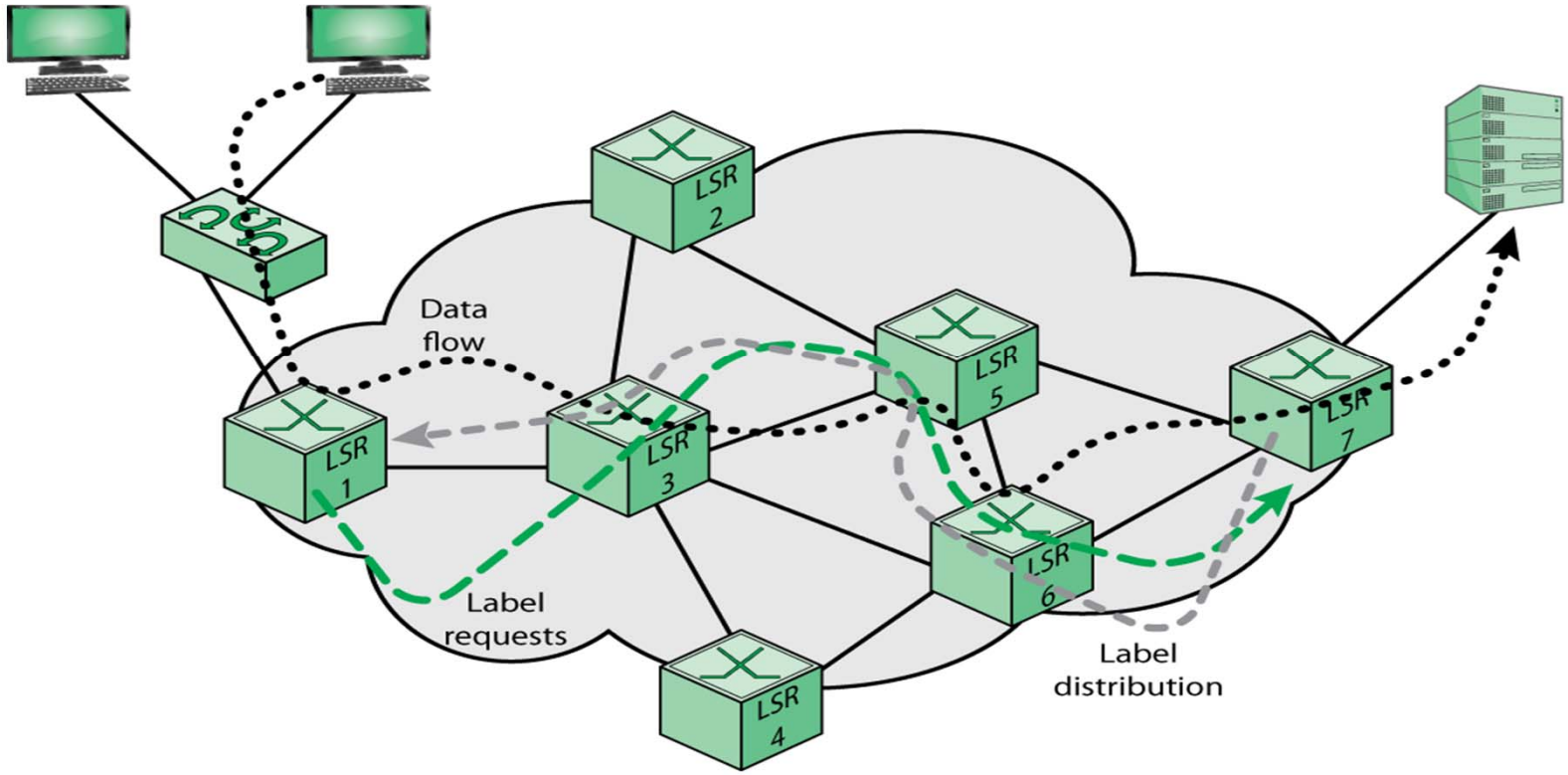
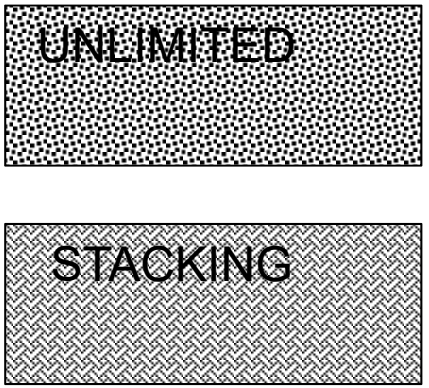


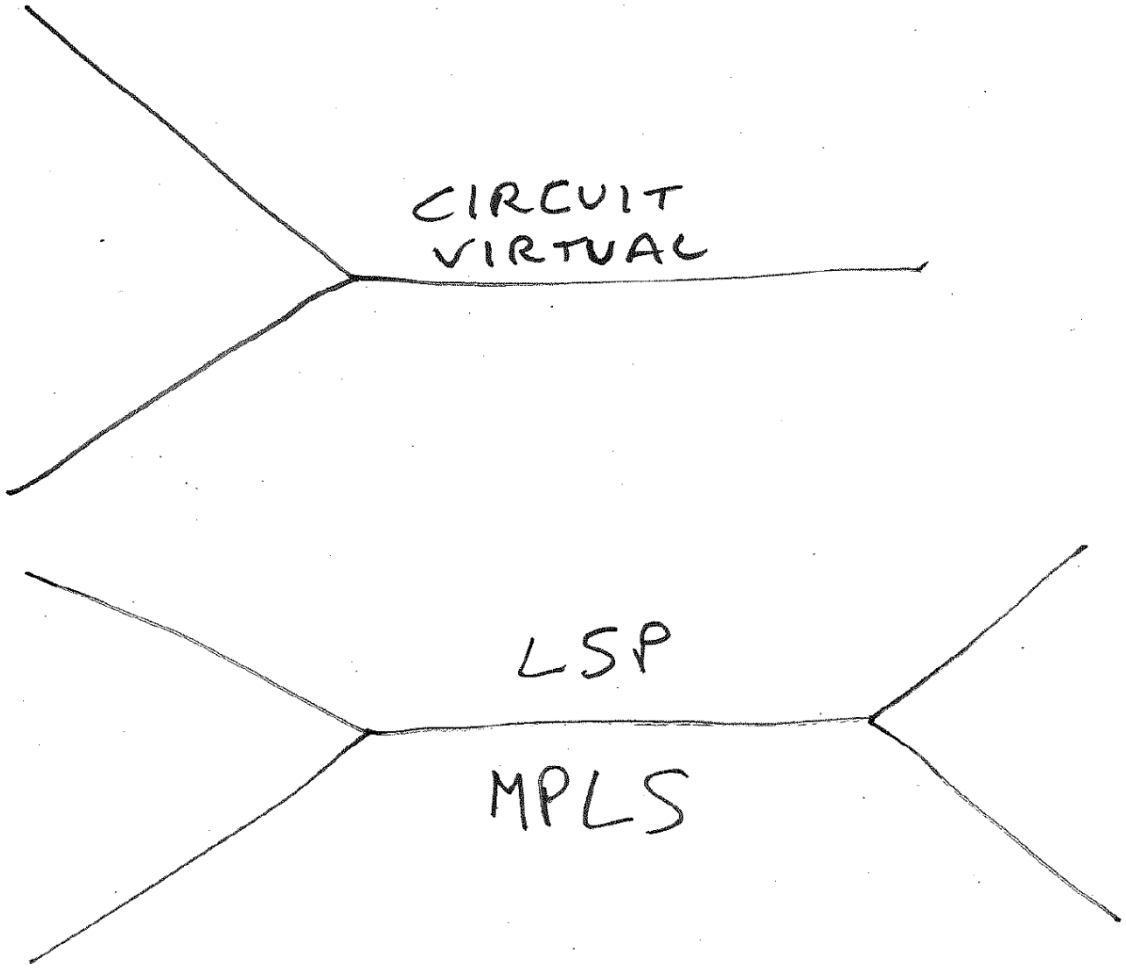
Figure 21.3 LSP Creation and Packet Forwarding through an MPLS Domain

Label Stacking

- One of the most powerful features of MPLS
  - Processing is always based on the top label
  - At any LSR a label may be removed or added
- Allows creation of tunnels
  - Tunnel refers to traffic routing being determined by labels
- Provides considerable flexibility
- Unlimited stacking

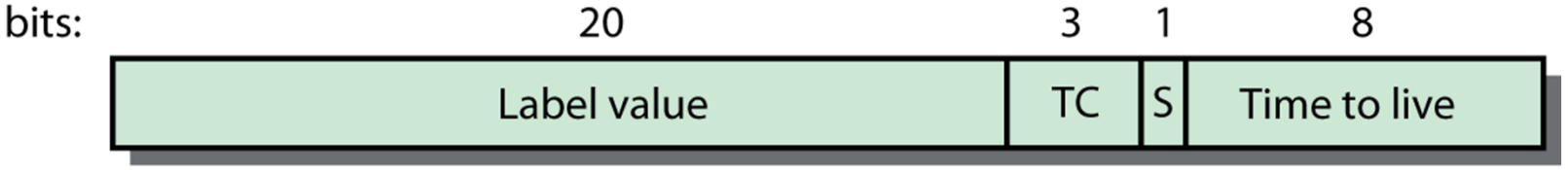


LSP with label Stacking



Label Format

- defined in RFC 3032
- 32-bit field consisting of:
- Label value
- Traffic class (TC)
- S
- Time to live (TTL)



TC = traffic class
S = bottom of stack bit

Figure 21.4 MPLS Label Format

Label Placement

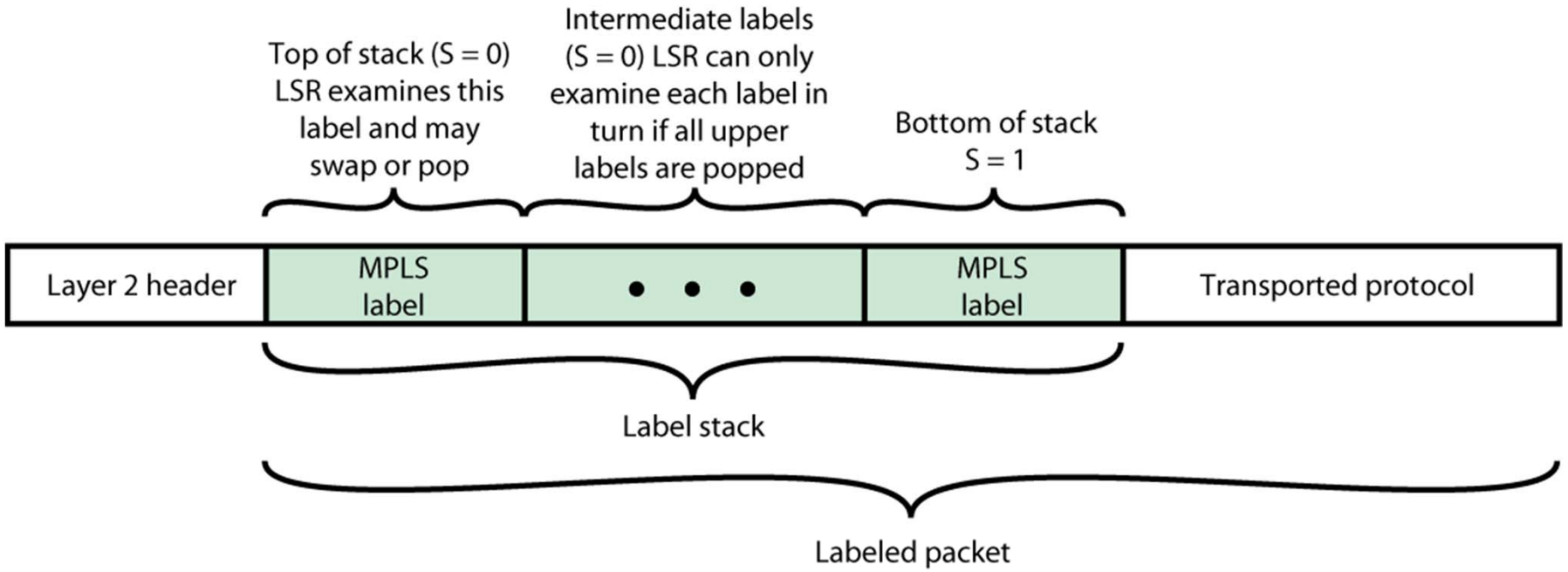
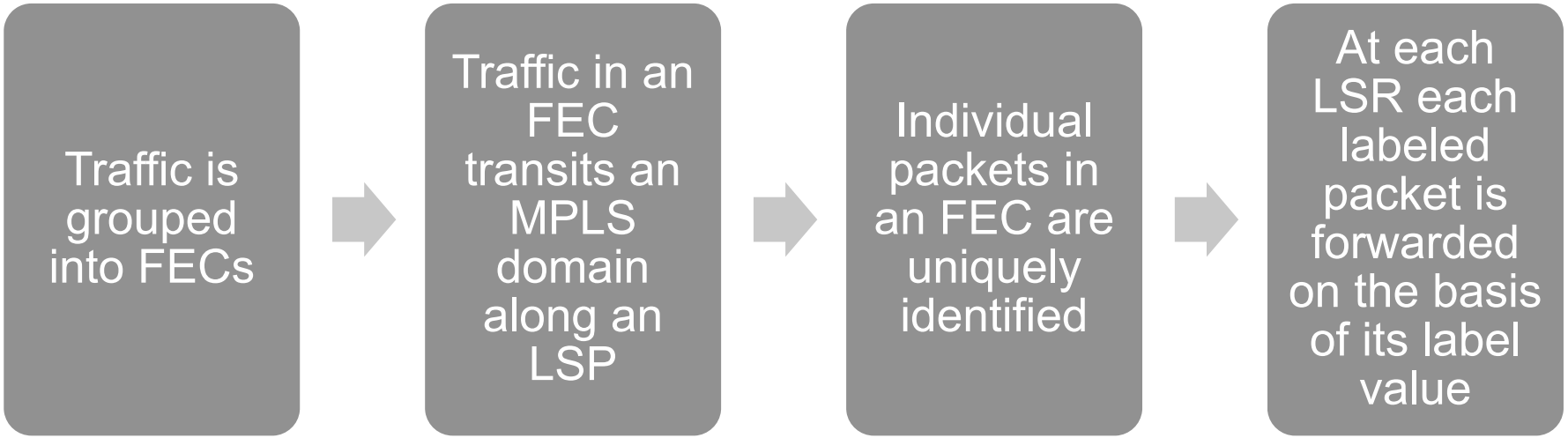


Figure 21.5 Encapsulation for Labeled Packet

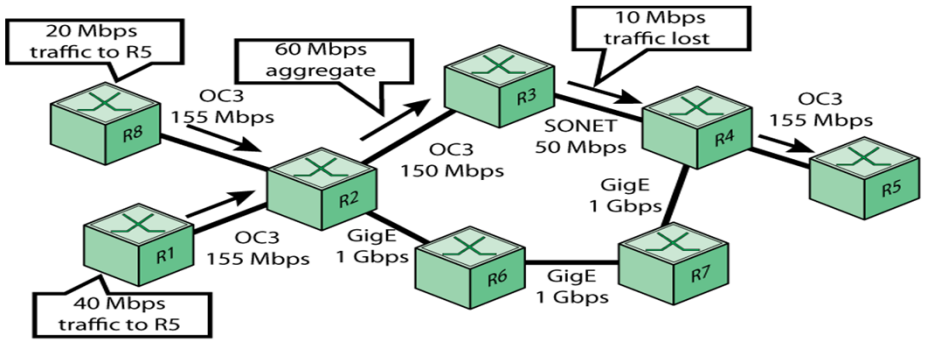
FECs, LSPs, and Labels



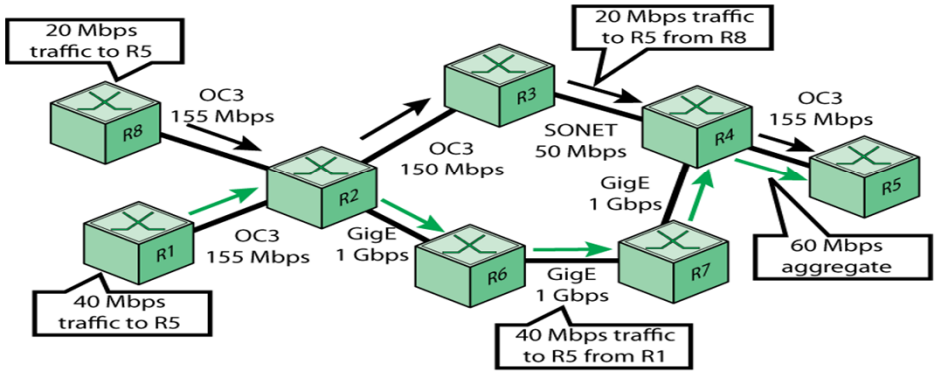
Traffic Engineering

- RFC 2702
- Allocate traffic to the network to maximize utilization of the network capacity
- Ensure the most desirable route through the network while meeting QoS requirements

Example of Traffic Engineering



(a) A shortest-path solution



(b) A traffic-engineered solution

Figure 21.9 Traffic Engineering Example

Elements of MPLS Traffic Engineering (MPLS TE)

- Information distribution
  - A link state protocol is necessary to discover the topology of the network
- Path calculation
  - Shortest path through a network that meets the resource requirements of the traffic flow
- Path setup
  - Signaling protocol to reserve the resources for a traffic flow and to establish the LSP
- Traffic forwarding
  - Accomplished with MPLS using the LSP

RSVP – TE Operation

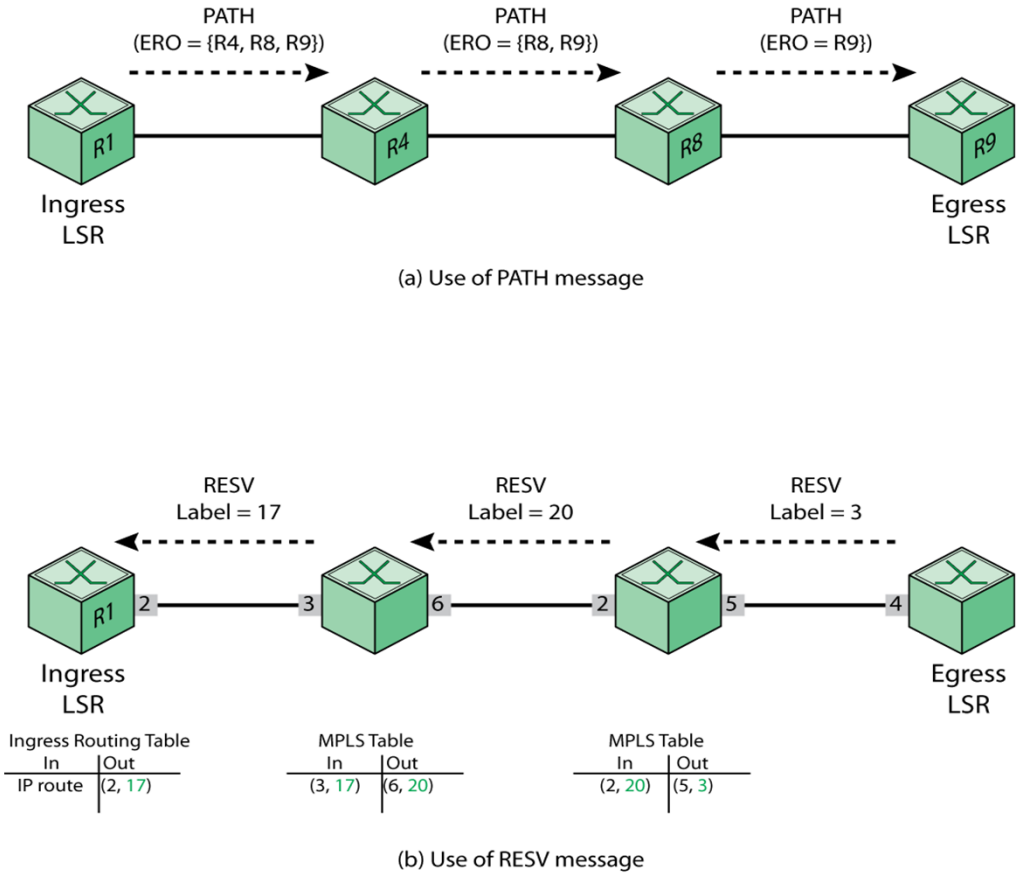


Figure 21.11 RSVP-TE Operation

Virtual Private Network (VPN)

- Private network configured within a public network in order to take advantage of management facilities of larger networks

- Traffic designated as VPN traffic can only go from a VPN source to a destination in the same VPN

Widely used by enterprises to:

- Create wide area networks (WANs)
- Provide site-to-site communications to branch offices
- Allow mobile user to dial up their company LANs

Layer 2 VPN

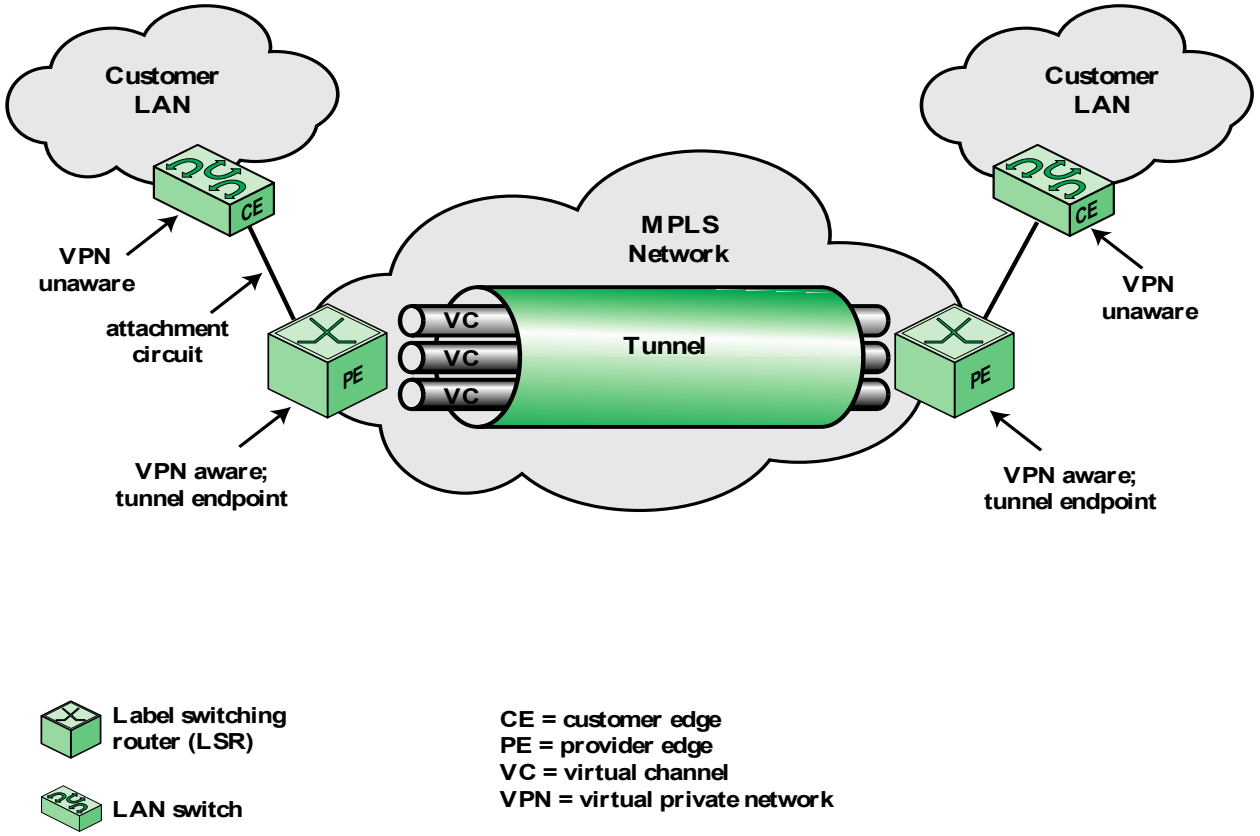
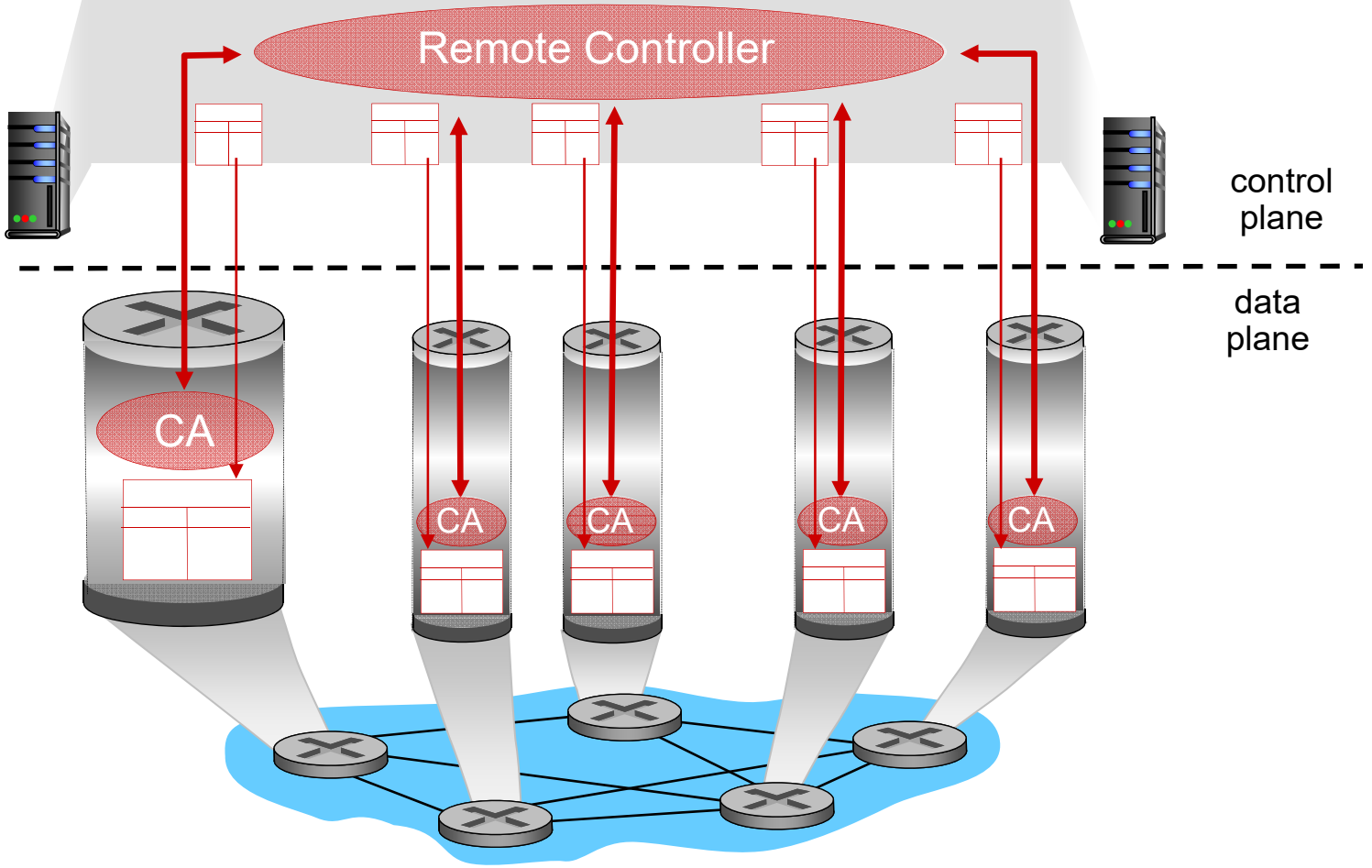


Figure 23.12 Layer 2 VPN Concepts

3.4 Software Defined Networking (SDN)

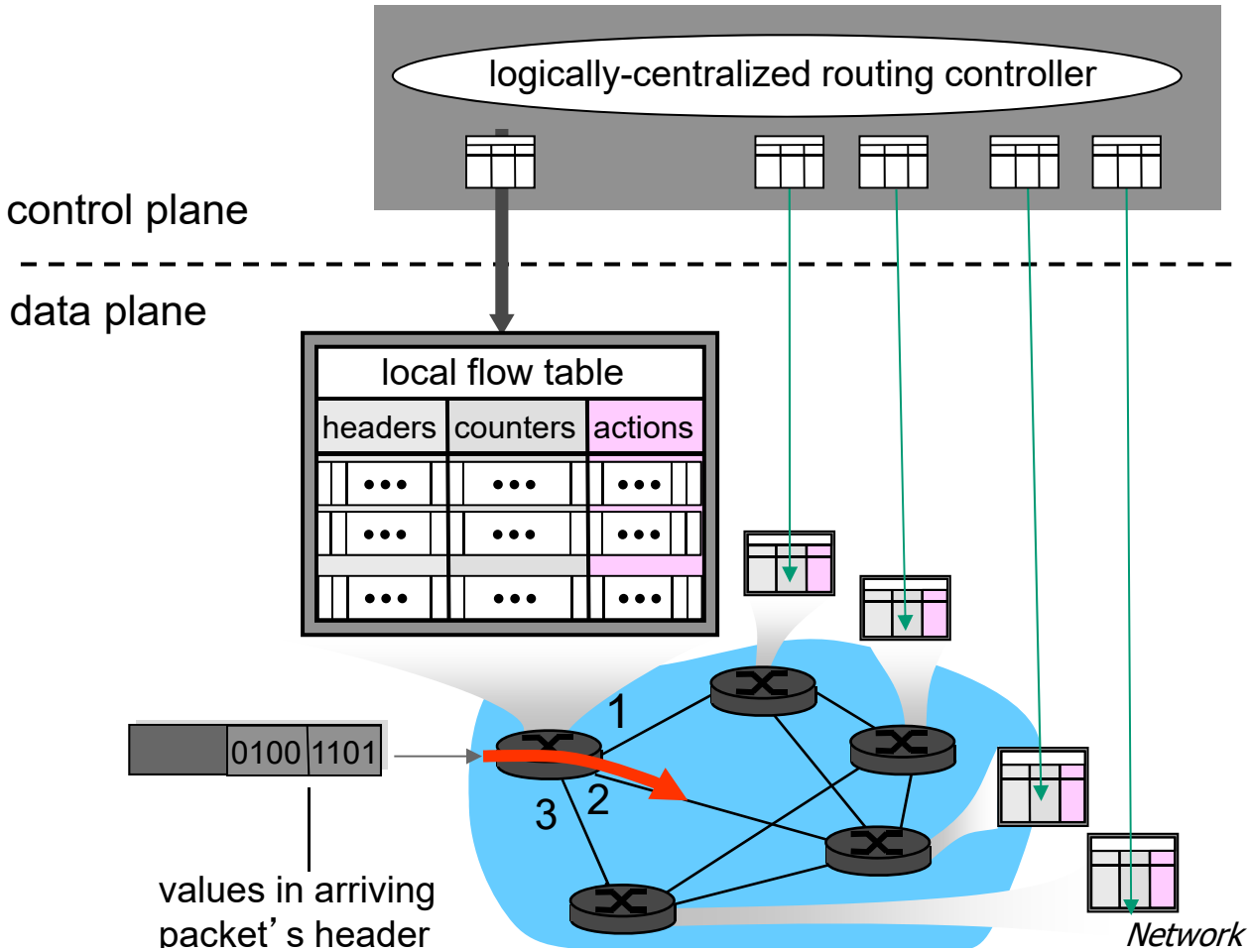
Logically centralized control plane

A distinct (typically remote) controller interacts with local control agents (CAs) in routers to compute forwarding tables



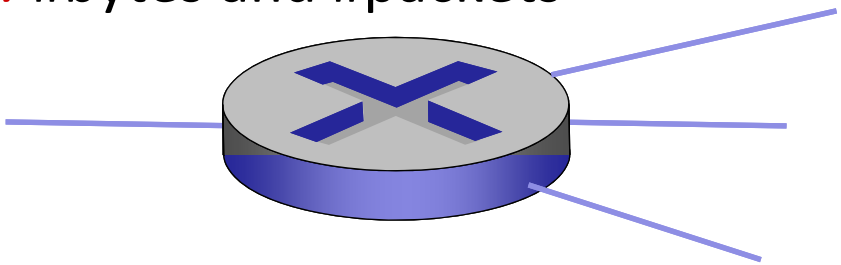
Generalized Forwarding and SDN

Each router contains a *flow table* that is computed and distributed by a *logically centralized* routing controller



Open Flow data plane abstraction

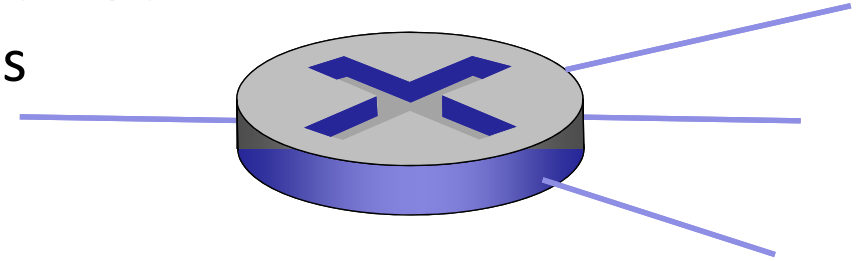
- *flow*: defined by header fields
- generalized forwarding: simple packet-handling rules
  - *Pattern:* match values in packet header fields
  - *Actions: for matched packet:* drop, forward, modify, matched packet or send matched packet to controller
  - *Priority*: disambiguate overlapping patterns
  - *Counters:* #bytes and #packets



Flow table in a router (computed and distributed by controller) define router's match+action rules

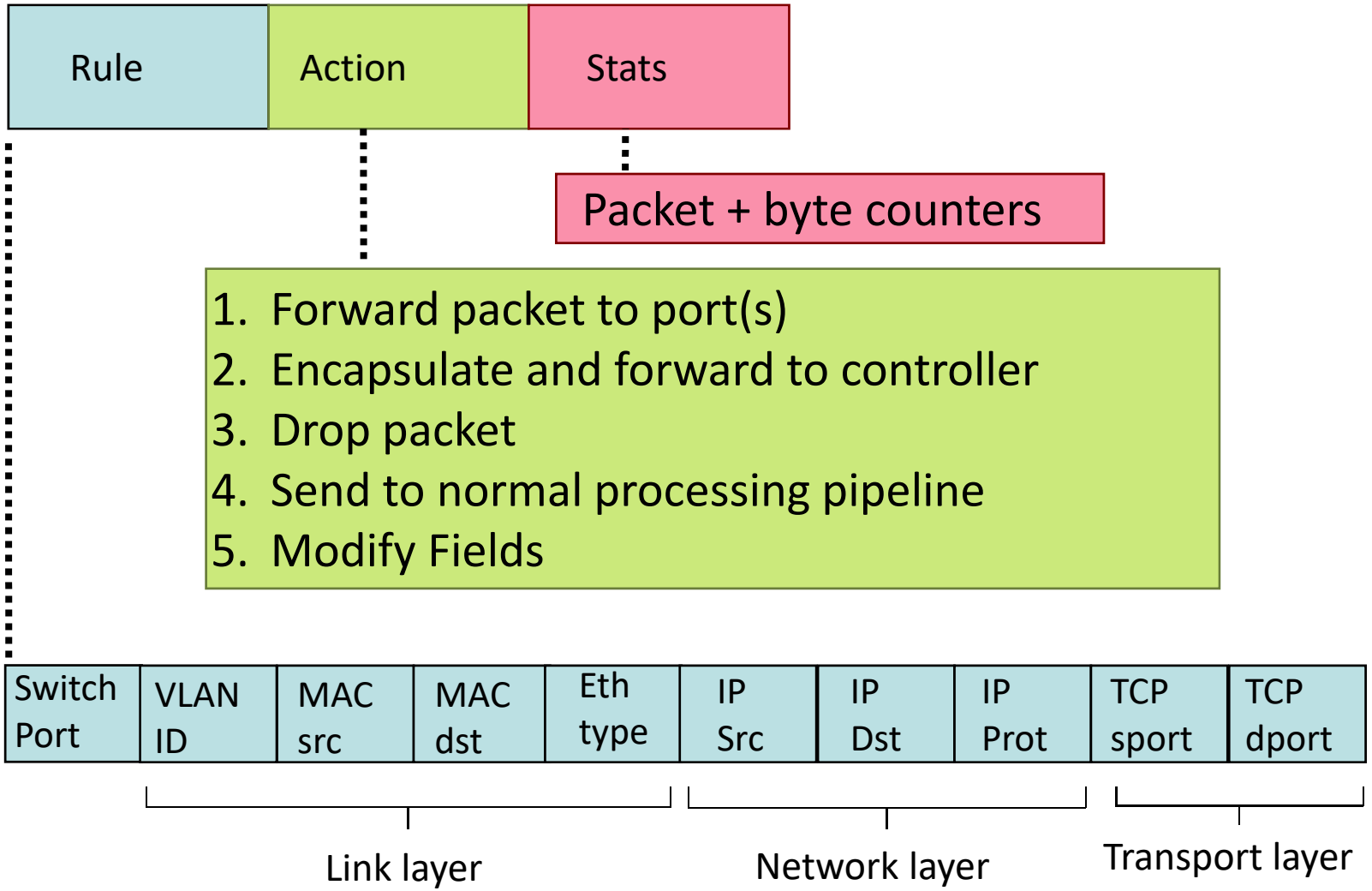
Open Flow data plane abstraction

- *flow*: defined by header fields
- generalized forwarding: simple packet-handling rules
  - *Pattern:* match values in packet header fields
  - *Actions: for matched packet:* drop, forward, modify, matched packet or send matched packet to controller
  - *Priority*: disambiguate overlapping patterns
  - *Counters:* #bytes and #packets



1. src=1.2.*.*, dest=3.4.5.* → drop
2. src = *.*.*.*, dest=3.4.*.* → forward(2)
3. src=10.1.2.3, dest=*.*.*.* → send to controller

Open Flow: Flow Table Entries



Examples (1)

Destination-based forwarding:

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	*	*	*	*	51.6.0.8	*	*	*	port6

IP datagrams destined to IP address 51.6.0.8 should be forwarded to router output port 6

Firewall:

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Forward
*	*	*	*	*	*	*	*	*	22	drop

do not forward (block) all datagrams destined to TCP port 22

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Forward
*	*	*	*	*	128.119.1.1	*	*	*	*	drop

do not forward (block) all datagrams sent by host 128.119.1.1

Examples (2)

Destination-based layer 2 (switch) forwarding:

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	22:A7:23: 11:E1:02	*	*	*	*	*	*	*	*	port3

layer 2 frames from MAC address 22:A7:23:11:E1:02 should be forwarded to output port 6

Open Flow abstraction

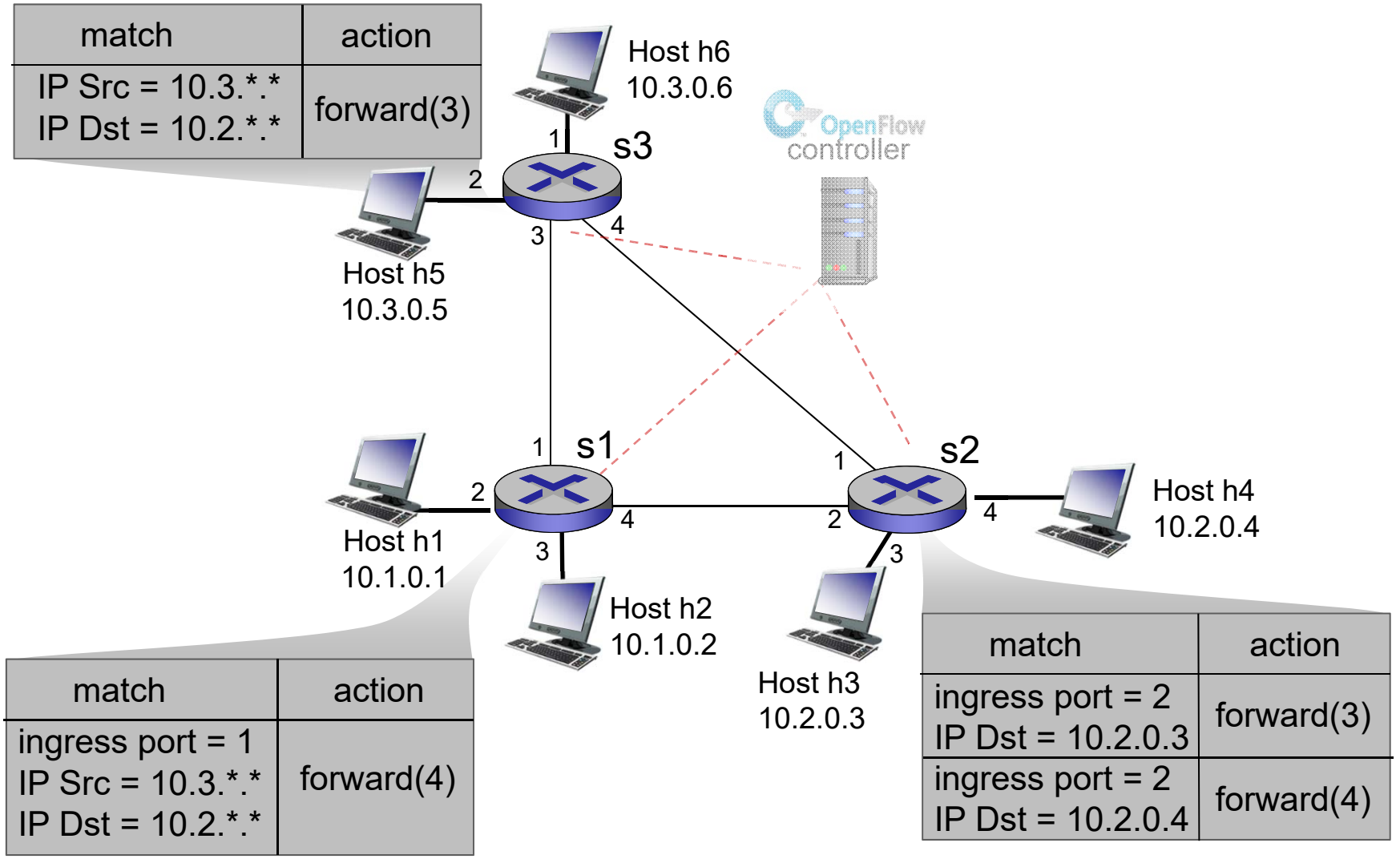
- *match+action:* unifies different kinds of devices

- Router
  - *match:* longest destination IP prefix
  - *action:* forward out a link
- Switch
  - *match:* destination MAC address
  - *action:* forward or flood

- Firewall
  - *match*: IP addresses and TCP/UDP port numbers
  - *action:* permit or deny
- NAT
  - *match:* IP address and port
  - *action:* rewrite address and port

OpenFlow example

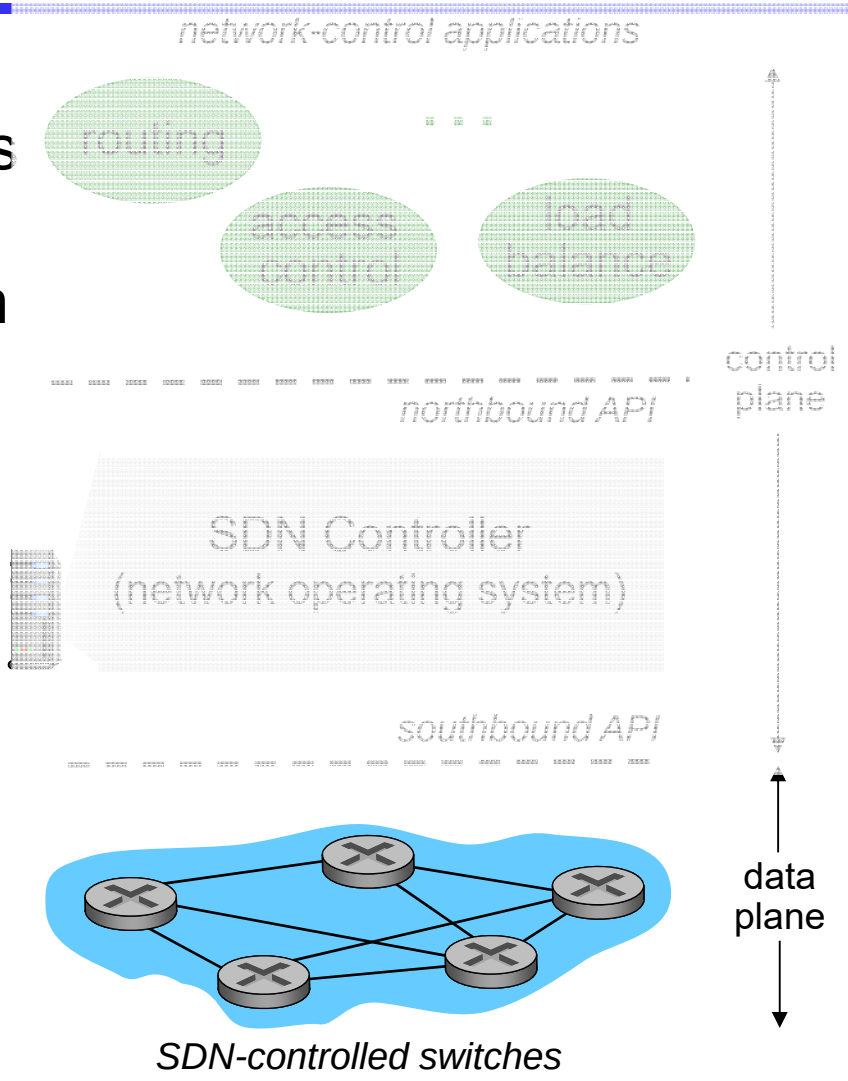
Example: datagrams from hosts h5 and h6 should be sent to h3 or h4, via s1 and from there to s2



SDN perspective: data plane switches

Data plane switches

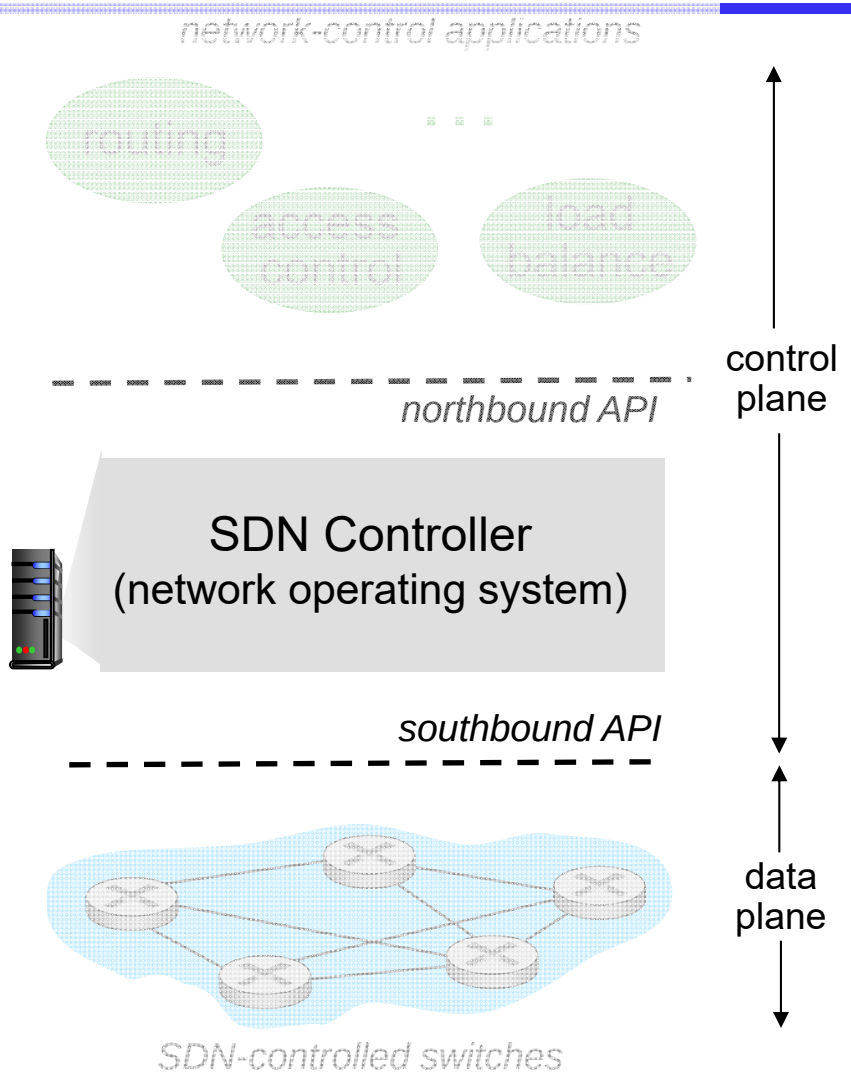
- fast, simple, commodity switches implementing generalized data-plane forwarding (Section 4.4) in hardware
- switch flow table computed, installed by controller
- API for table-based switch control (e.g., OpenFlow)
  - defines what is controllable and what is not
- protocol for communicating with controller (e.g., OpenFlow)



SDN perspective: SDN controller

SDN controller (network OS):

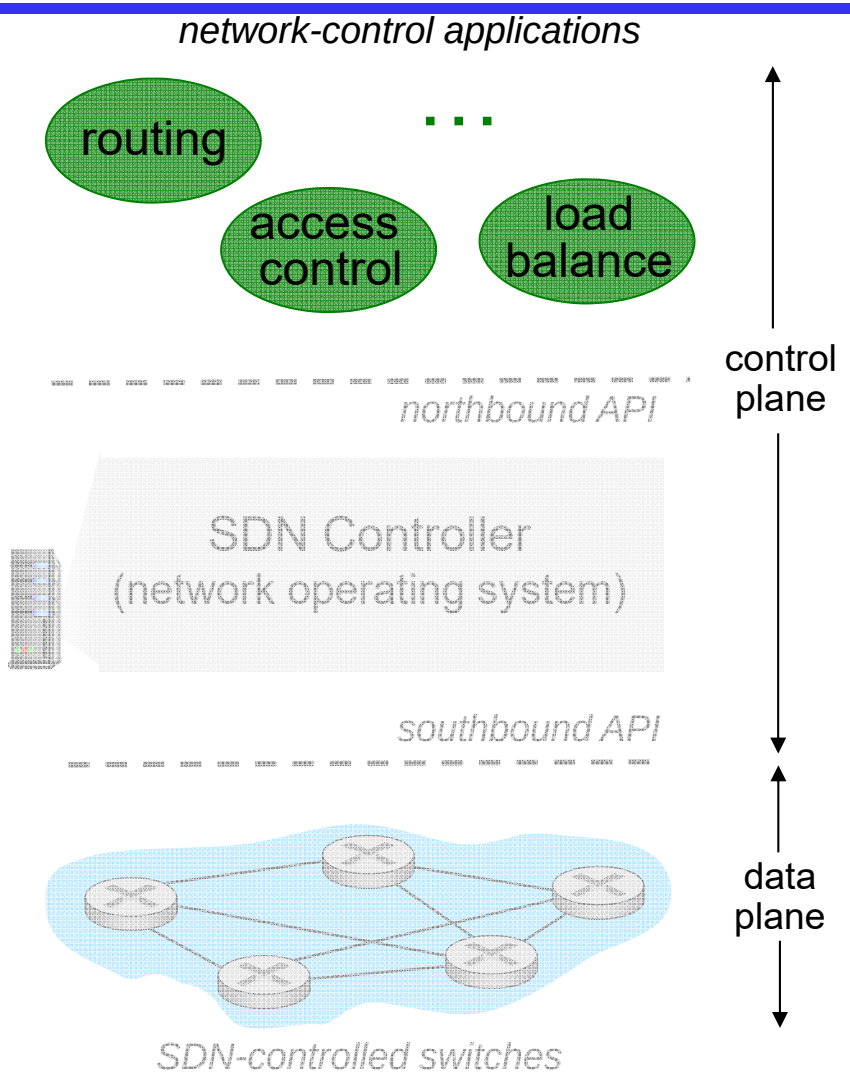
- maintain network state information
- interacts with network control applications "above" via northbound API
- interacts with network switches "below" via southbound API
- implemented as distributed system for performance, scalability, fault-tolerance, robustness



SDN perspective: control applications

network-control apps:

- "brains" of control: implement control functions using lower-level services, API provided by SDN controller
- *unbundled:* can be provided by 3rd party: distinct from routing vendor, or SDN controller

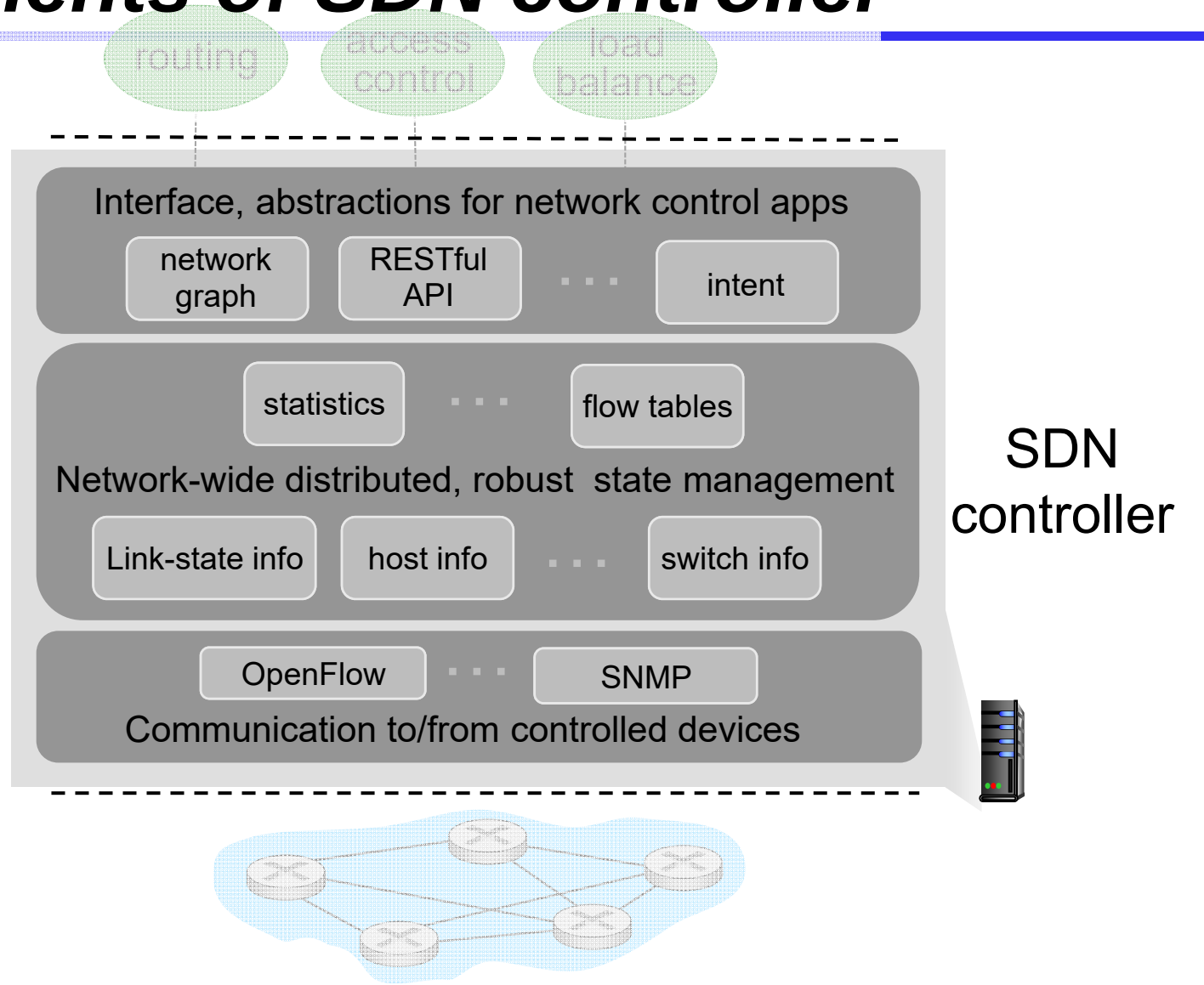


Components of SDN controller

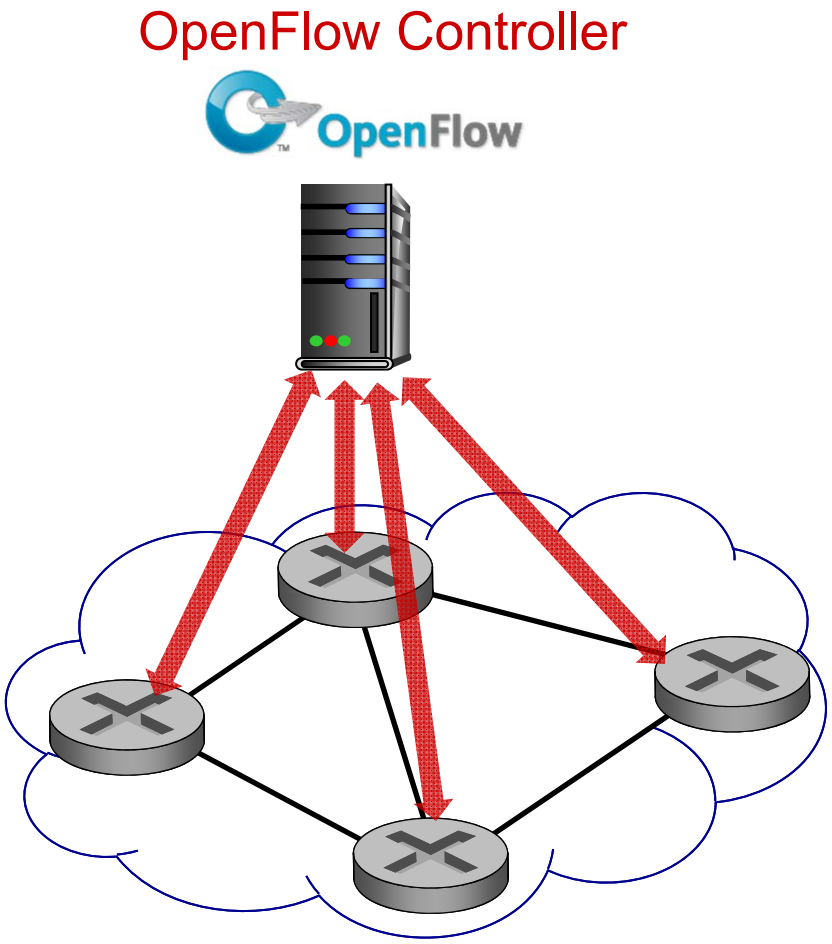
Interface layer to network control apps: abstractions API

Network-wide state management layer: state of networks links, switches, services: a *distributed database*

communication layer: communicate between SDN controller and controlled switches



OpenFlow protocol

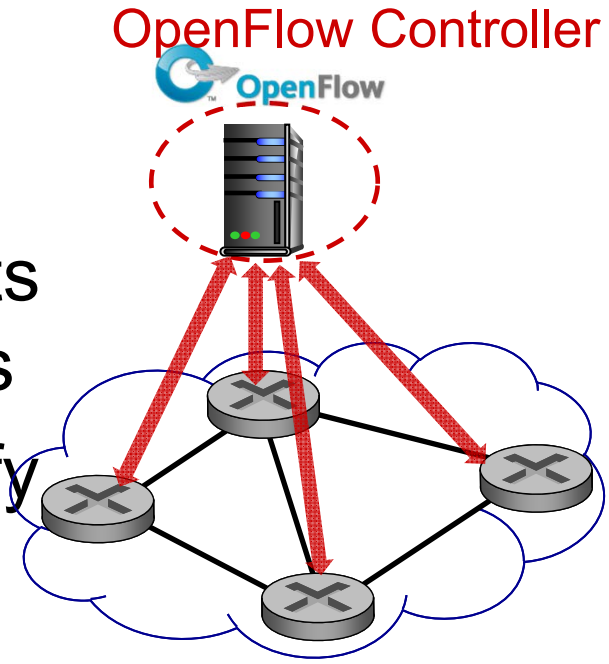


- operates between controller, switch
- TCP used to exchange messages
  - optional encryption
- three classes of OpenFlow messages:
  - controller-to-switch
  - asynchronous (switch to controller)
  - symmetric (misc)

OpenFlow: controller-to-switch messages

Key controller-to-switch messages

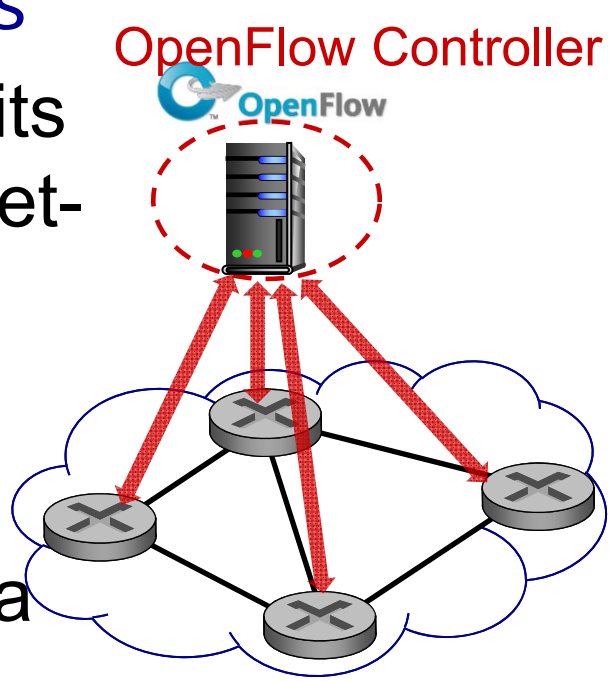
- *features:* controller queries switch features, switch replies
- *configure:* controller queries/sets switch configuration parameters
- *modify-state:* add, delete, modify flow entries in the OpenFlow tables
- *packet-out:* controller can send this packet out of specific switch port



OpenFlow: switch-to-controller messages

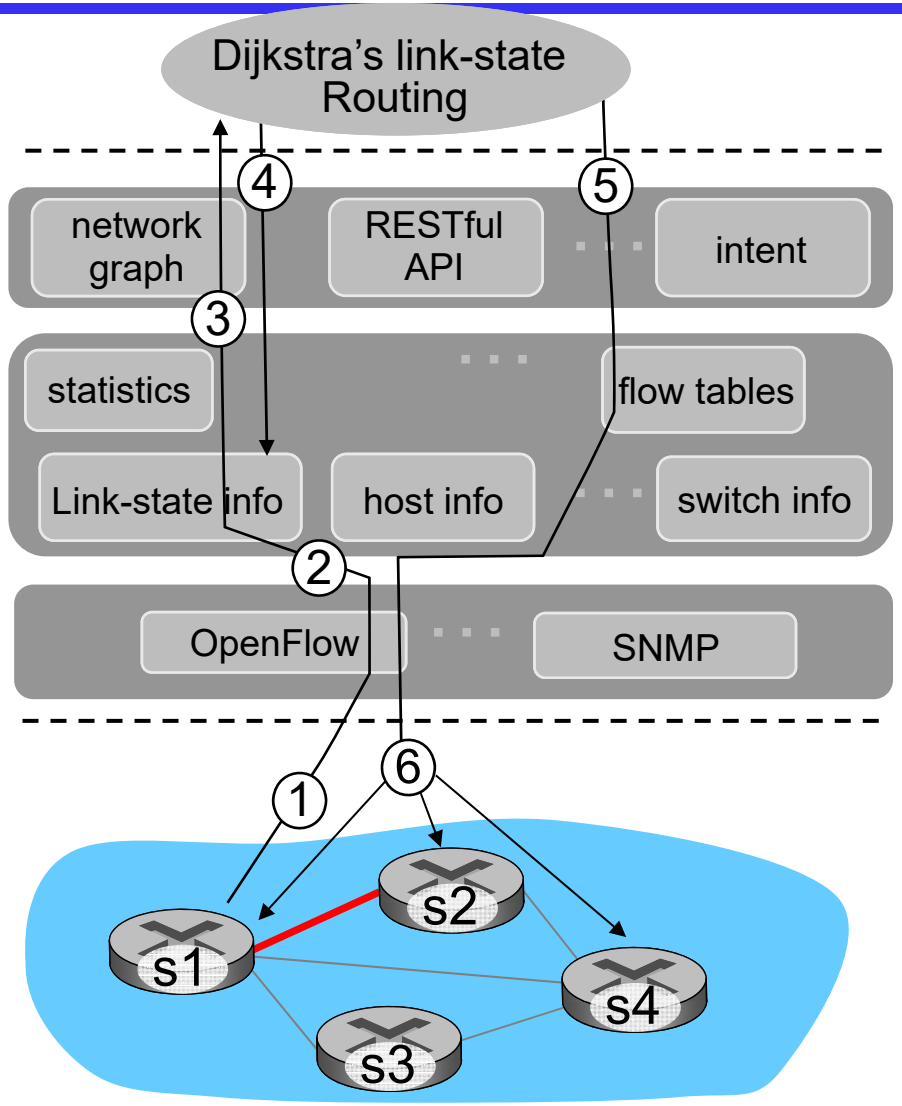
Key switch-to-controller messages

- *packet-in:* transfer packet (and its control) to controller. See packet-out message from controller
- *flow-removed:* flow table entry deleted at switch
- *port status:* inform controller of a change on a port.



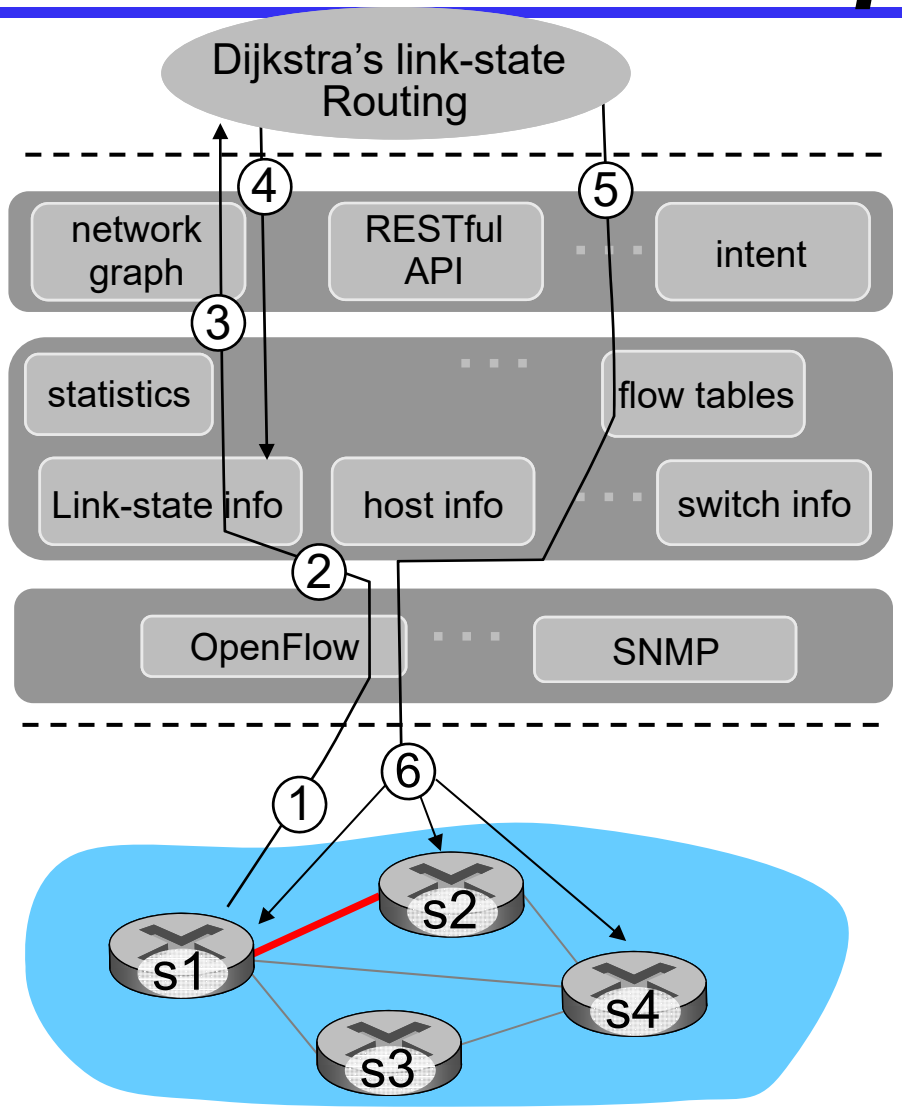
Fortunately, network operators don't "program" switches by creating/sending OpenFlow messages directly. Instead use higher-level abstraction at controller

SDN: control/data plane interaction example



1. S1, experiencing link failure using OpenFlow port status message to notify controller
2. SDN controller receives OpenFlow message, updates link status info
3. Dijkstra's routing algorithm application has previously registered to be called when ever link status changes. It is called.
4. Dijkstra's routing algorithm access network graph info, link state info in controller, computes new routes

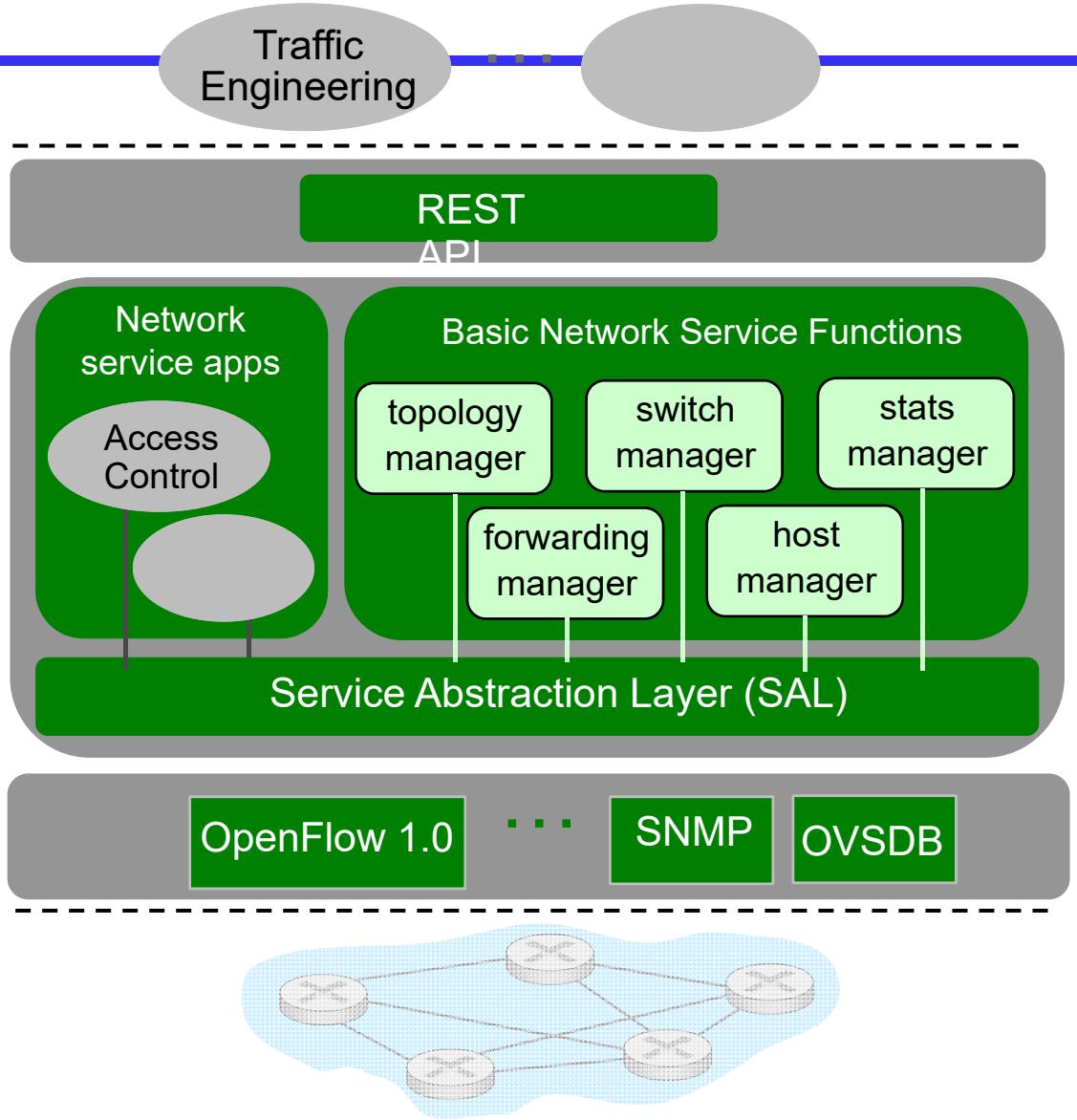
SDN: control/data plane interaction example



⑤ link state routing app interacts with flow-table-computation component in SDN controller, which computes new flow tables needed

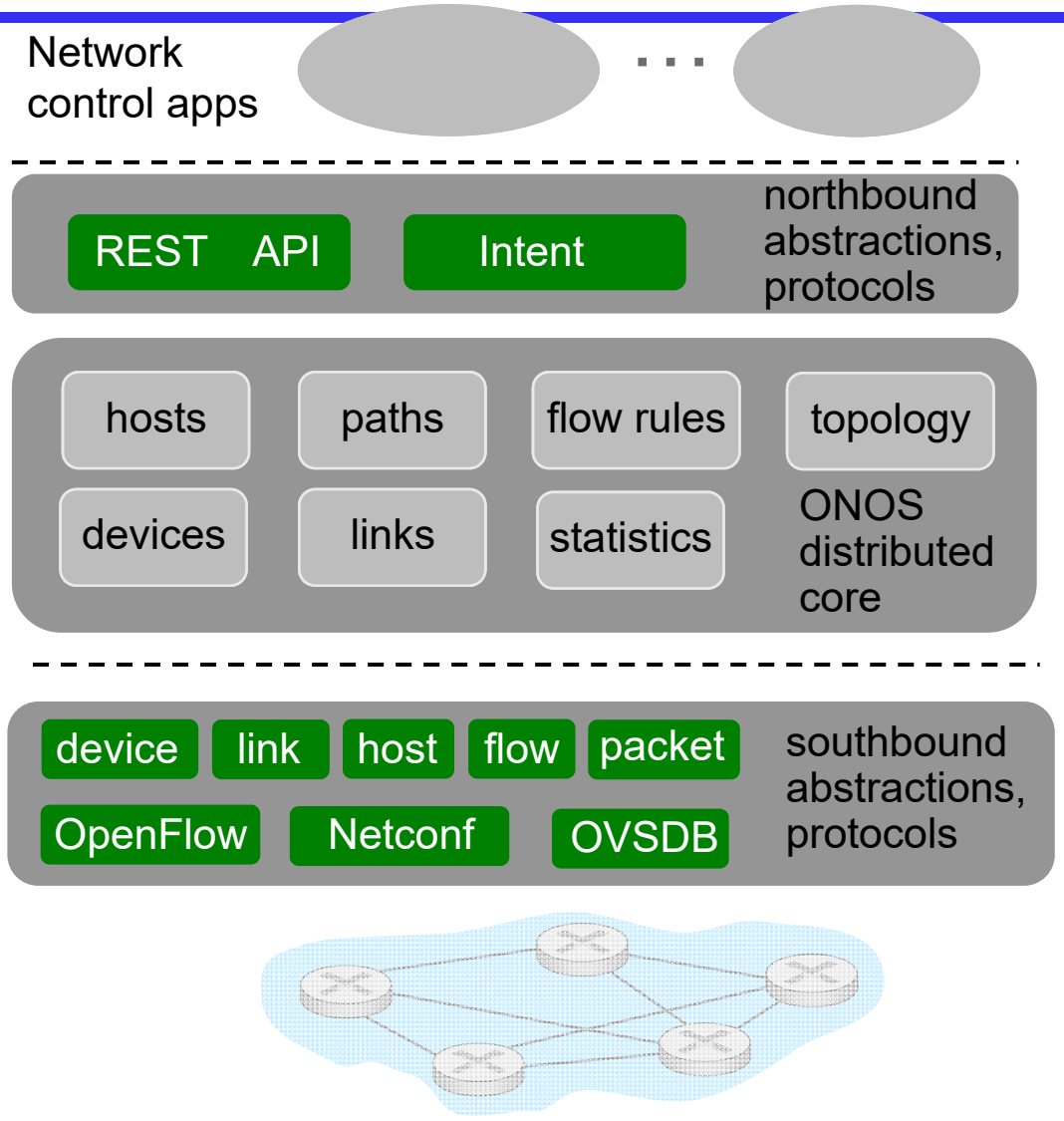
⑥ Controller uses OpenFlow to install new tables in switches that need updating

OpenDaylight (ODL) controller



- ODL Lithium controller
- network apps may be contained within, or be external to SDN controller
- Service Abstraction Layer: interconnects internal, external applications and services

ONOS controller



- control apps separate from controller
- intent framework: high-level specification of service: what rather than how
- considerable emphasis on distributed core: service reliability, replication performance scaling