AOT LAB
Agent and **O**bject **T**echnology **Lab**
Dipartimento di Ingegneria dell'Informazione
Università degli Studi di Parma

Computer Network

Wide Area Network

Prof. Agostino Poggi

WAN

- Bridging of any distance
- Usually for covering of a country or a continent
- Topology normally is irregular due to orientation to current needs
- Usually quite complex interconnections of sub-networks which are owned by different operators
- No broadcast, but point-to-point connections

WAN

- LAN technologies cannot be used for building networks able to be extended arbitrarily far or to handle arbitrarily many computers
  - Distance limitations even with extensions
  - Broadcast is a problem
- Need other technologies for realizing WAN
- WAN technologies replace shared media with packet switches and point-to-point connections

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WAN Components

- Point-to-point long-distance connections
  - Throughput depends on estimated traffic
  - Number depends on reliability needed
- Packet switches
  - Special purpose computer systems
  - Connect to other packet switches and to computers
  - Forward packets
- Computers

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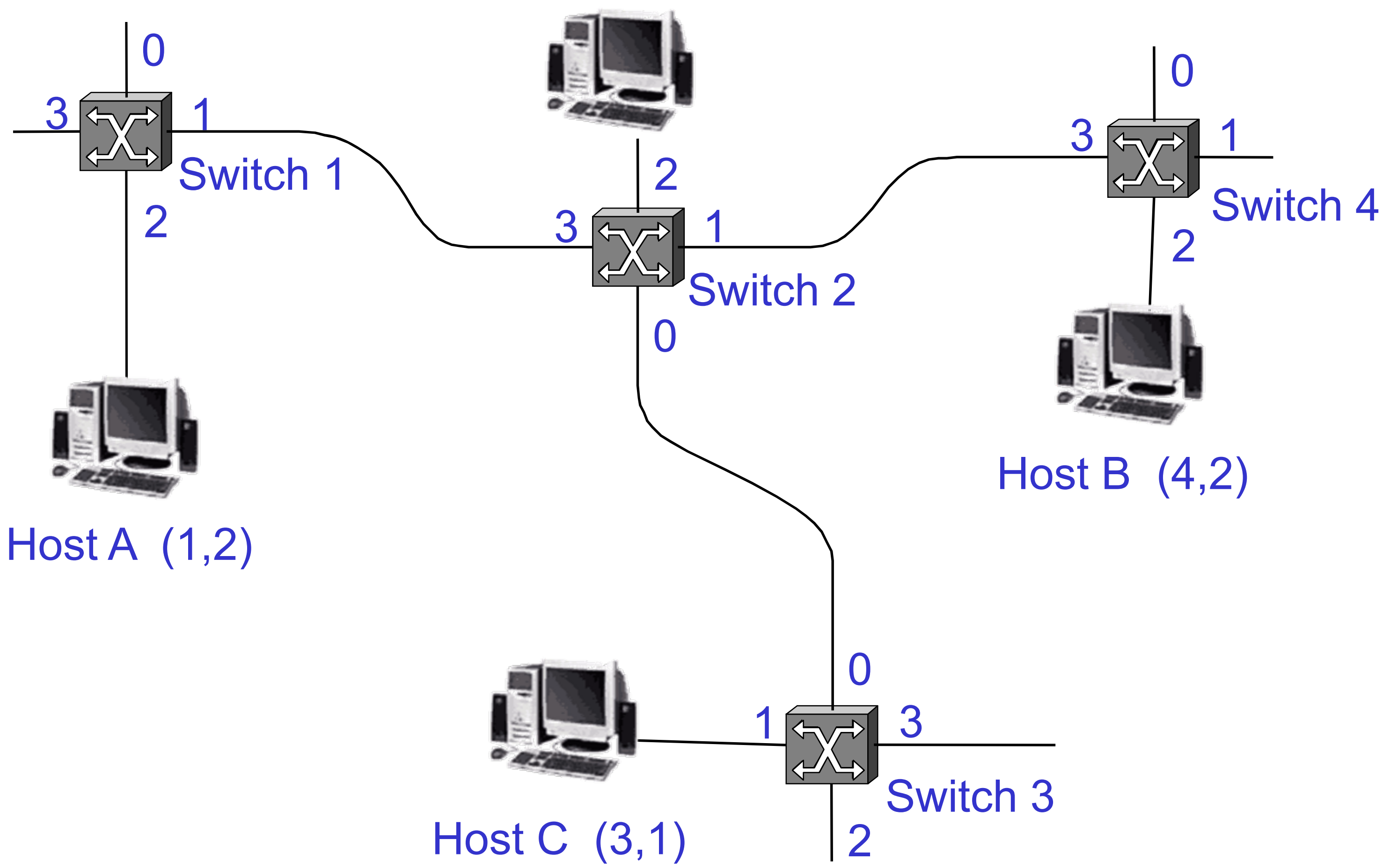
Store and Forward

- Basic paradigm used in packet switched network
- Packet
  - Contains destination address
    - Packet switch number
    - Computer number
- Switch
  1. Stores packet in memory
  2. Examines destination
  3. Forwards packet
     - Using routing table
     - Routing table gives next hop

Store and Forward



Flow Control

- Needed because
  - Sending computer system is faster than receiving computer
  - Sending application is faster than receiving application
- Synchronizes computers
- Avoids congestion
- Two forms
  - Stop-and-go
  - Sliding window

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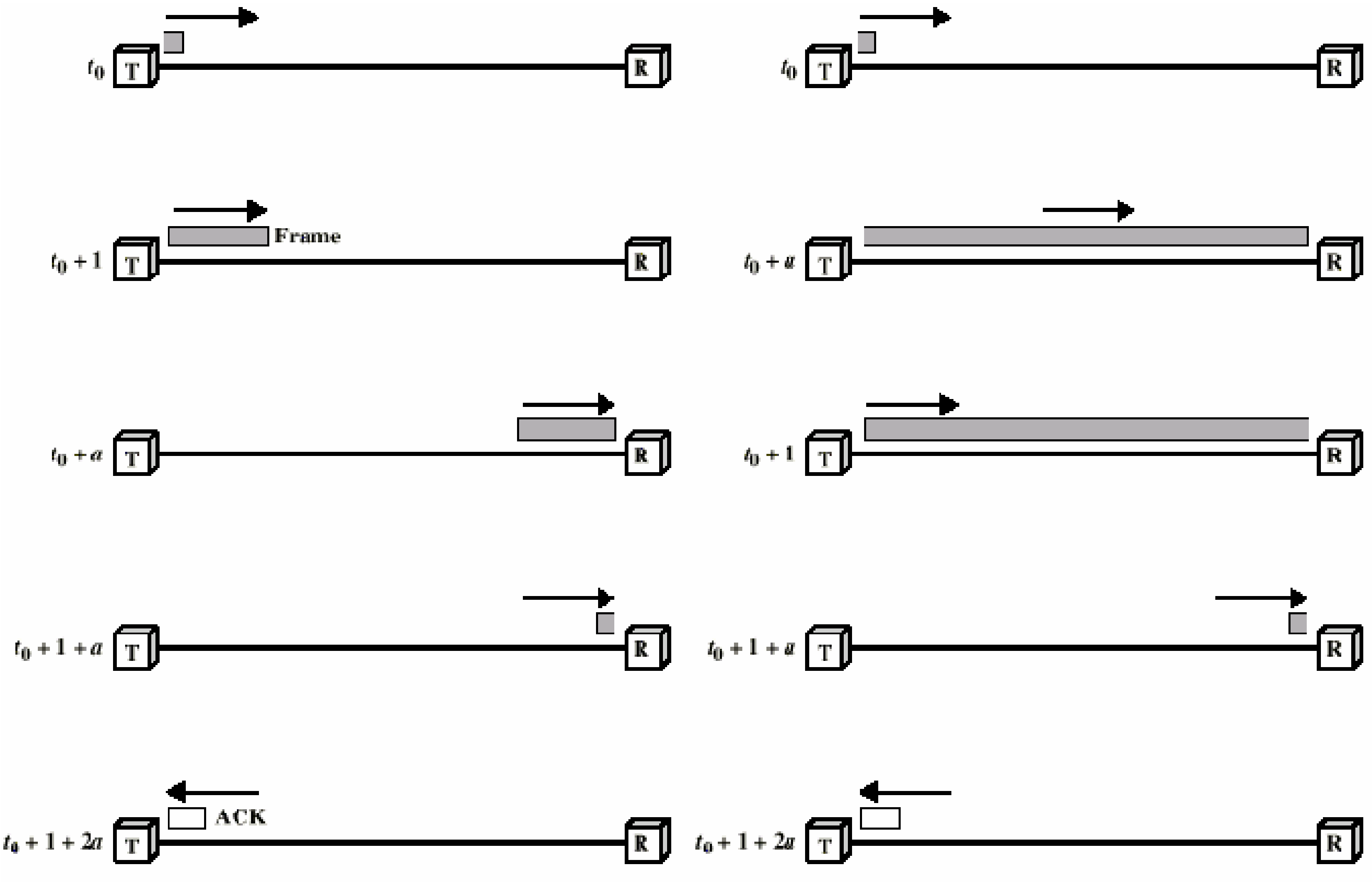
Stop-and-Go

- Sender
  1. Transmits one packet
  2. Waits for signal from receiver
- Receiver
  1. Receives and consumes packet
  2. Transmits signal to sender
- Inefficient

Stop-and-Go

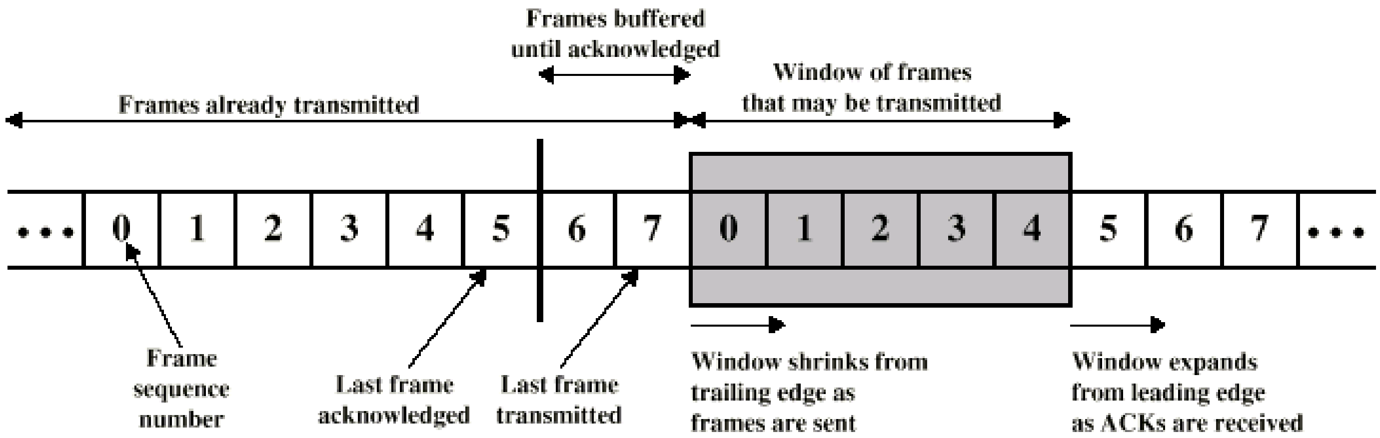


(a) $a > 1$ (b) $a < 1$

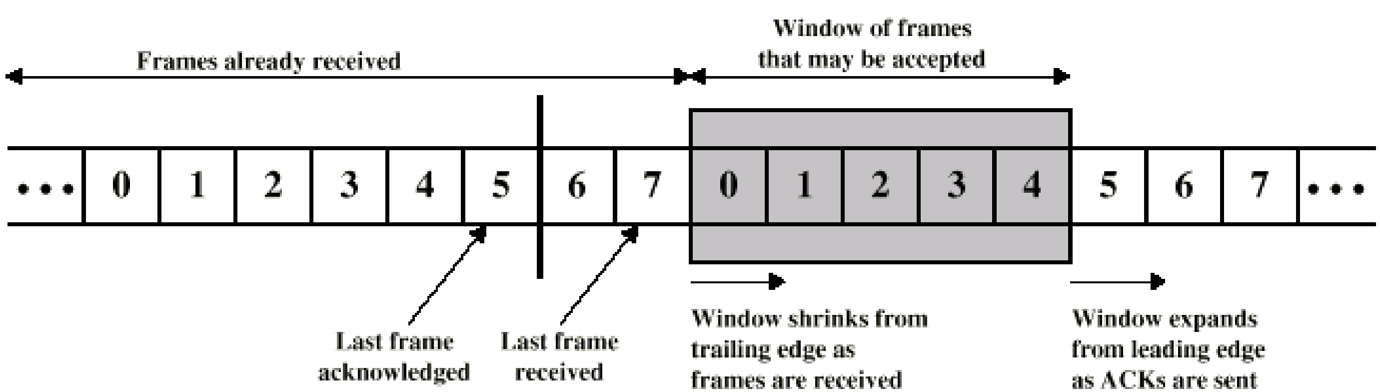
Sliding Window

- Receiver
  - Establishes multiple buffers and informs sender
- Sender
  1. Transmits packets for all available buffers
     - Each frame is numbered
  2. Only waits if no signal arrive before transmission completes
- Receiver
  - Send signals as packets arrive
    - Signals include number of next packet expected

Sliding Window

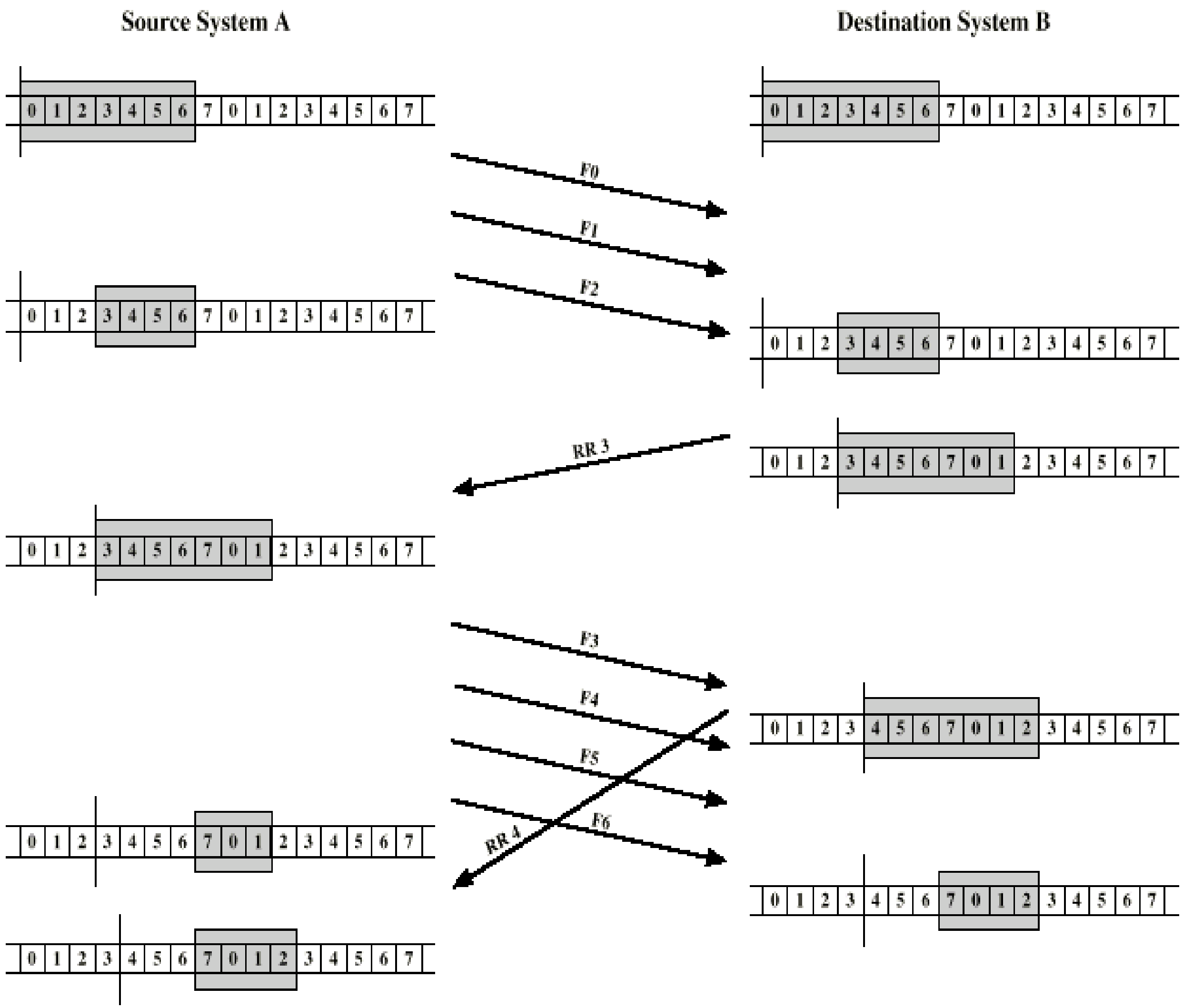


(a) Sender's perspective



(b) Receiver's perspective

Sliding Window

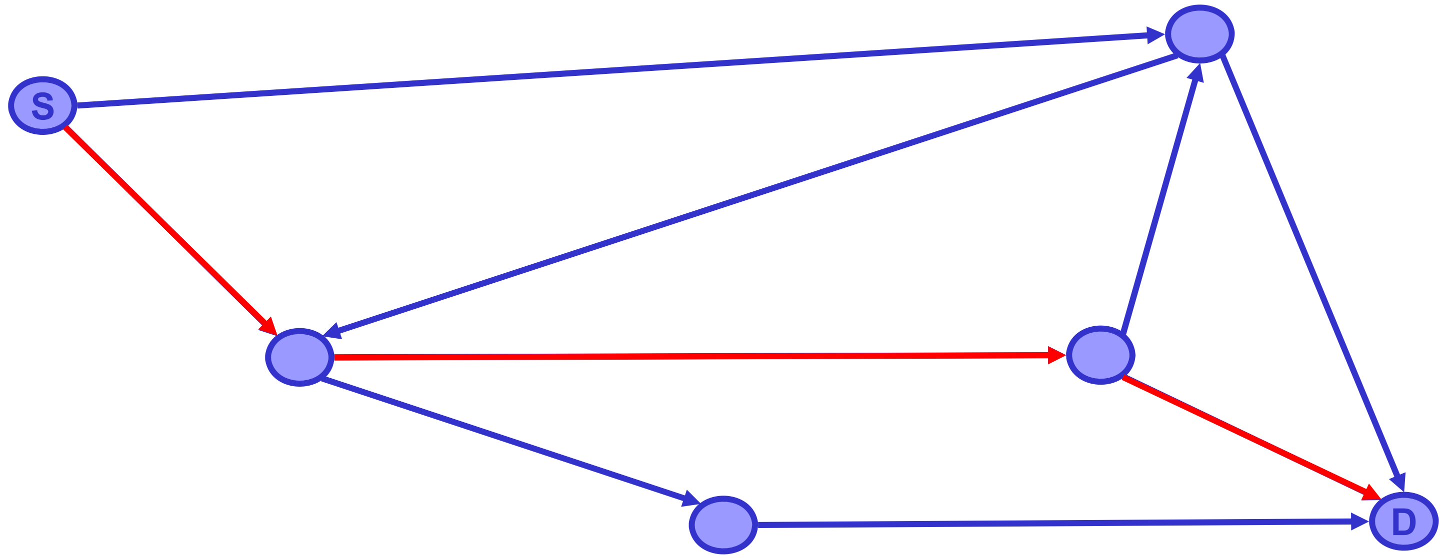


Sliding Window

- Sliding window techniques can be enhanced
  - Receiver can acknowledge frames without permitting further transmission (Receive Not Ready)
    - Must send a normal acknowledge to resume
  - If duplex, use piggybacking
    - If no data to send
      - Use acknowledgement frame
    - If data but no acknowledgement to send
      - Send last acknowledgement number again

Routing

- Finds a path (sequence of routers) from a source to a destination
- Uses it to transport data to the destination
- Usually is based on the building of a routing table for each router of the net



Routing Algorithm Desiderata

- Optimality
- Fairness
- Stability
- Robustness
- Correctness
- Simplicity

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- Packets are routed in two ways
  - Connection-Oriented
    - Packets follow the same route
    - Fixed routes are called Virtual Circuits
    - Think to telephone call
  - Connectionless
    - Each packet is independently handled
    - Packets contain address of destination
    - No setup required before transmission of data
    - No cleanup required after transmission of data
    - Think to postcards

Connection-Oriented

- Sender
  1. Requests connection to receiver
  2. Waits for network to form connection
  3. Leaves connection in place while sending data
  4. Terminates connection when no longer needed

- Network
  1. Receives connection request
  2. Forms path to specified destination and informs sender
  3. Transfers data across connection
  4. Removes connection when sender requests

Connection-Oriented

- Permanent Virtual Circuit (PVC)
  - Entered manually
  - Survives reboot
  - Usually persists months
- Switched Virtual Circuit (SVC)
  - Requested dynamically
  - Initiated by application
  - Terminated when application exits

Connection-Oriented Vs. Connectionless

- Connection-Oriented
  - More intelligent in network
  - Can reserve bandwidth
  - Connection setup overhead
  - State in packet switches
  - Well-suited to real-time applications

- Connectionless
  - Less overhead
  - Permits asynchronous use
  - Allows broadcast/multicast

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Routing Algorithm Classification

- Global view
  - Graph of entire network (i.e., routers, links)
- Local view
  - Partial knowledge of remote parts of network
- Centralized
  - One node maintains view and distributes routes to other nodes
- Decentralized
  - All nodes maintain view
- Static
  - Infrequent route changes
  - Infrequent view update (i.e., static link costs)
- Dynamic
  - Frequent periodic route changes
  - Frequent view update; (i.e., dynamic link costs)
- Manual
  - Tables created by hand
- Automatic
  - Software creates/updates tables

Dynamic Algorithms Subclasses

- Isolated
  - Each router makes its routing decisions using only the local information it has on hand
  - Routers do not even exchange information with their neighbors
- Centralized
  - A centralized node makes all routing decisions
  - The centralized node has access to global information
- Distributed
  - Each router makes its routing decisions using a combination of local and global information

Isolated Routing

- Flooding
  - Routers forward packets to all ports except the input port
- Hot potato
  - Routers choose output line with the shortest queue
- Backward learning
  - Routers use information stored in normal packets (i.e., source address and number of hops) to learn shortest path to each source

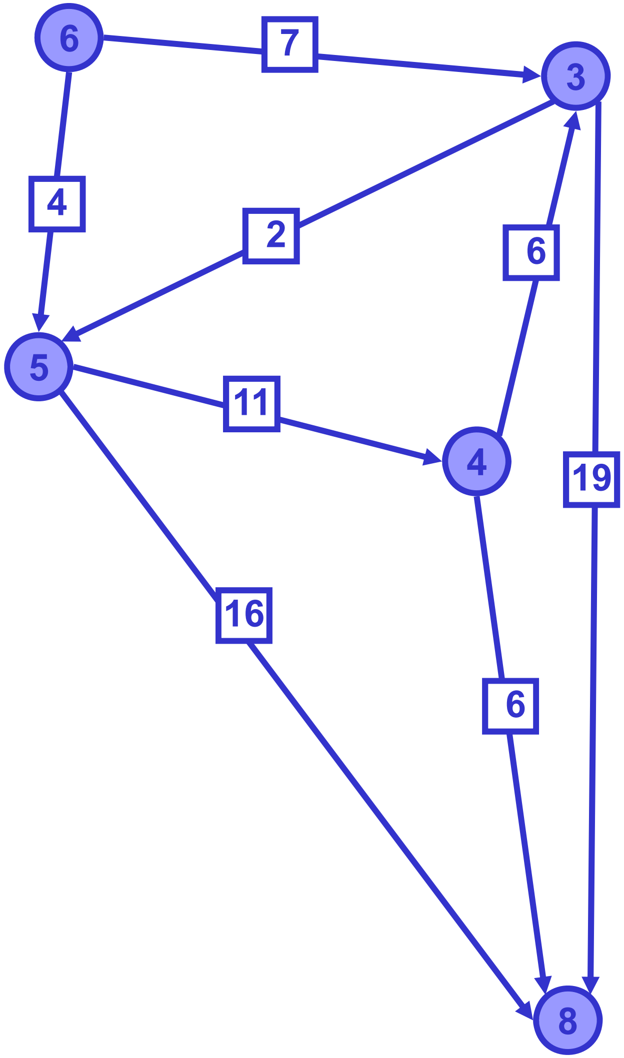
Advantages / Disadvantages

- All
  - Simple
- Backward learning
  - Efficient

- Flooding and Hot potato
  - Some routers receive a packet multiple times
  - Packets can go round in loops forever
  - Inefficient
- Flooding
  - High traffic
- Hot potato
  - Long delay
- Backward learning
  - Only deal with good news, not bad

Computer Network Graph Model

- Nodes model switches and computers
- Edges model connections
- Label on edges represents distance
  - Geographic distance
  - Economic cost
  - Inverse of capacity



Distributed Routing Algorithms

- Routers use graph theory algorithms to compute routing tables

- Two main routing algorithms
  - Distance Vector
  - Link-State

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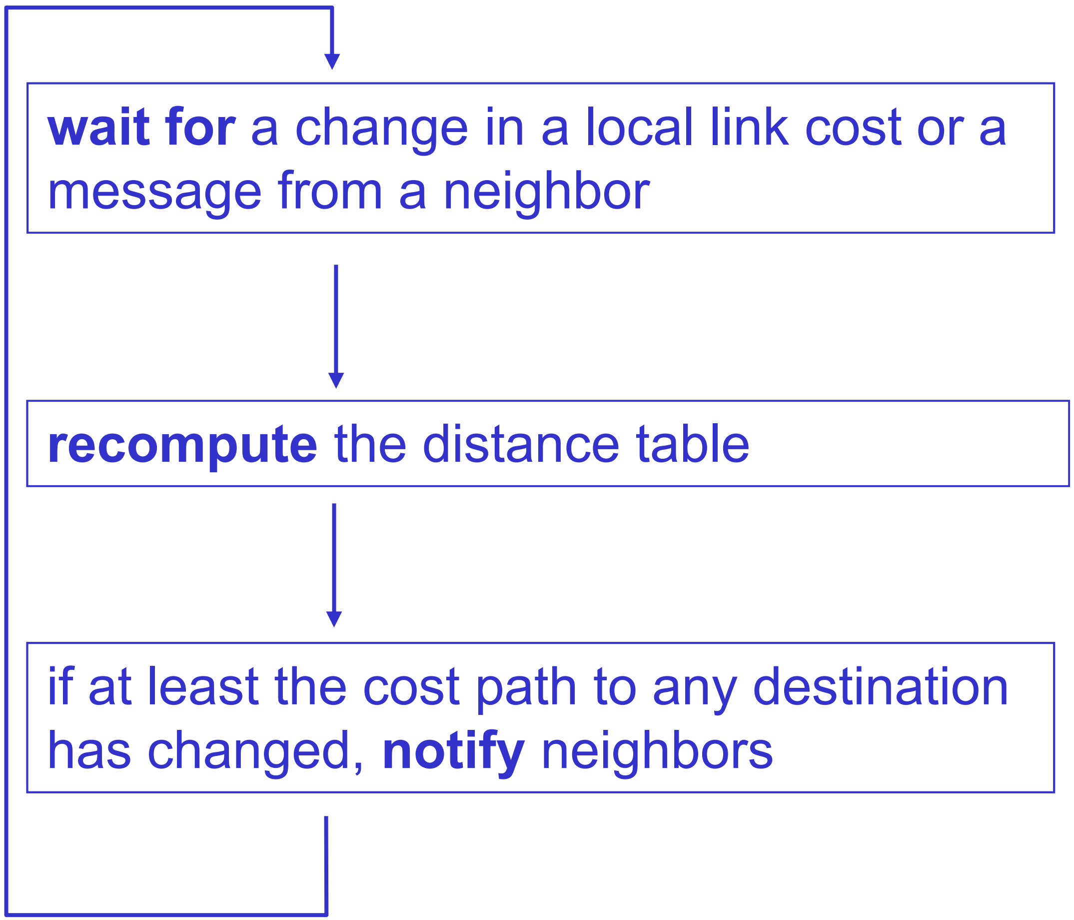
Distance Vector

- Periodic two-way exchange between neighbors caused by local link cost change or the reception of a message from a neighbor
- Sender
  - Sends a list of pairs (destination and distance) when distance change
- Receiver
  1. Compares each pair to local routes
  2. Changes routes if better path exists
- Exchanges stop when costs converge

Distance Vector



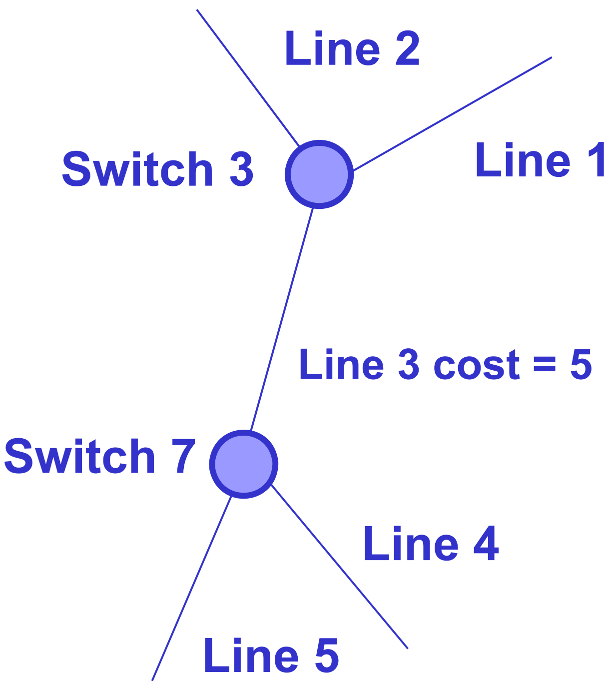
Bellman-Ford Algorithm

- Let
  - **N** denotes the set of nodes in the graph
  - **s** denotes the node for which compute paths
  - neighbors(s) denotes the neighbors of node s
  - $\mathbf{C_{ij}}$ denotes a non-negative cost/weight for the path from the node i to the node j
  - $\mathbf{P_j}$ denotes the next hop from the node s toward the node j
- Then the algorithm is defined as follows

```
∀ n є N  /* initialization */
    if n ≠ s
        C_sn = ∞
    else
        C_sn = 0

repeat
  ∀ n є neighbor(s)
     ∀ z є N
         if C_sz > C_sn + C_nz then
             C_sz = C_sn + C_nz
             P_z = n
until converge
```

Distance Vector



Switch 3

A	H	C	L
1	5	25	3
2	3	20	2
3	0	0	0
4	2	15	3
5	7	55	1
6	4	23	1
7	1	5	3
...	...	...	

Line 3

A	H	C
1	6	30
2	4	25
3	1	5
4	3	20
5	8	60
6	5	28
7	2	10
...	...	...

Distance Vector

Line 4

A	H	C
1	3	15
2	5	44
3	2	11
4	3	11
5	4	30
6	2	14
7	2	10
…	…	…

Line 0

A	H	C
7	0	0

Switch 7

A	H	C	L
1	3	15	4
2	3	25	5
3	1	5	3
4	3	11	4
5	4	30	4
6	2	14	5
7	0	0	0
…	…	…	

Line 5

A	H	C
1	4	20
2	3	25
3	3	43
4	4	20
5	4	30
6	2	14
7	2	10
…	…	…

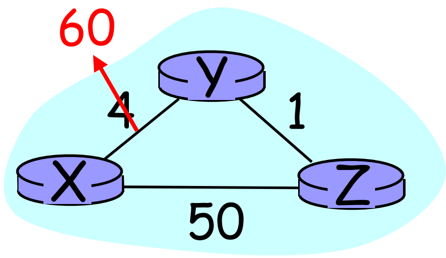
Line 3

A	H	C
1	6	30
2	4	25
3	1	5
4	3	20
5	8	60
6	5	28
7	2	10
…	…	…

Distance Vector Problems

- Black hole
  - A node receives a packet for which it does not know a path (usually during transient)
- Bouncing effect
  - Some packets loop into a ring of nodes (usually during transient)
- Count to infinity
  - When a node becomes unreachable or assumes a bad value, the related cost may rise slowly toward the new value
  - Solution is to fix a cost threshold for setting a node as unreachable

Count to Infinity



Y to X		Y to X		Y to X		Y to X		Y to X	
X	4	X	60	X	60	X	60	X	60
Z	6	Z	6	Z	6	Z	8	Z	8

Z to X		Z to X		Z to X		Z to X		Z to X	
X	50	X	50	X	50	X	50	X	50
Y	5	Y	5	Y	7	Y	7	Y	9

Time

Cost link between x and y changes

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Distance Vector Pros & Cons

- Distance Vector is easy to be implemented, but
  - Nodes have not topology information
  - Difficulties to predict its behavior for large network
  - High complexity (between $O(N^2)$ and $O(N^3)$)
    - Hierarchical network structure
  - Slow convergence

Link-State Routing

- Periodic broadcast of information on link status
- Pair of switches
  1. Test link between them
  2. Broadcast link status message
- Receiver
  1. Receives status messages
  2. Computes new routes
  3. Uses Dijkstra's algorithm
- Process performed whenever needed
  - When connections die / reappear

Dijkstra's Algorithm

- Input
  - Graph with weighted edges
  - Goal node
- Output
  - Set of shortest paths from goal node to the other nodes
  - Cost of each path

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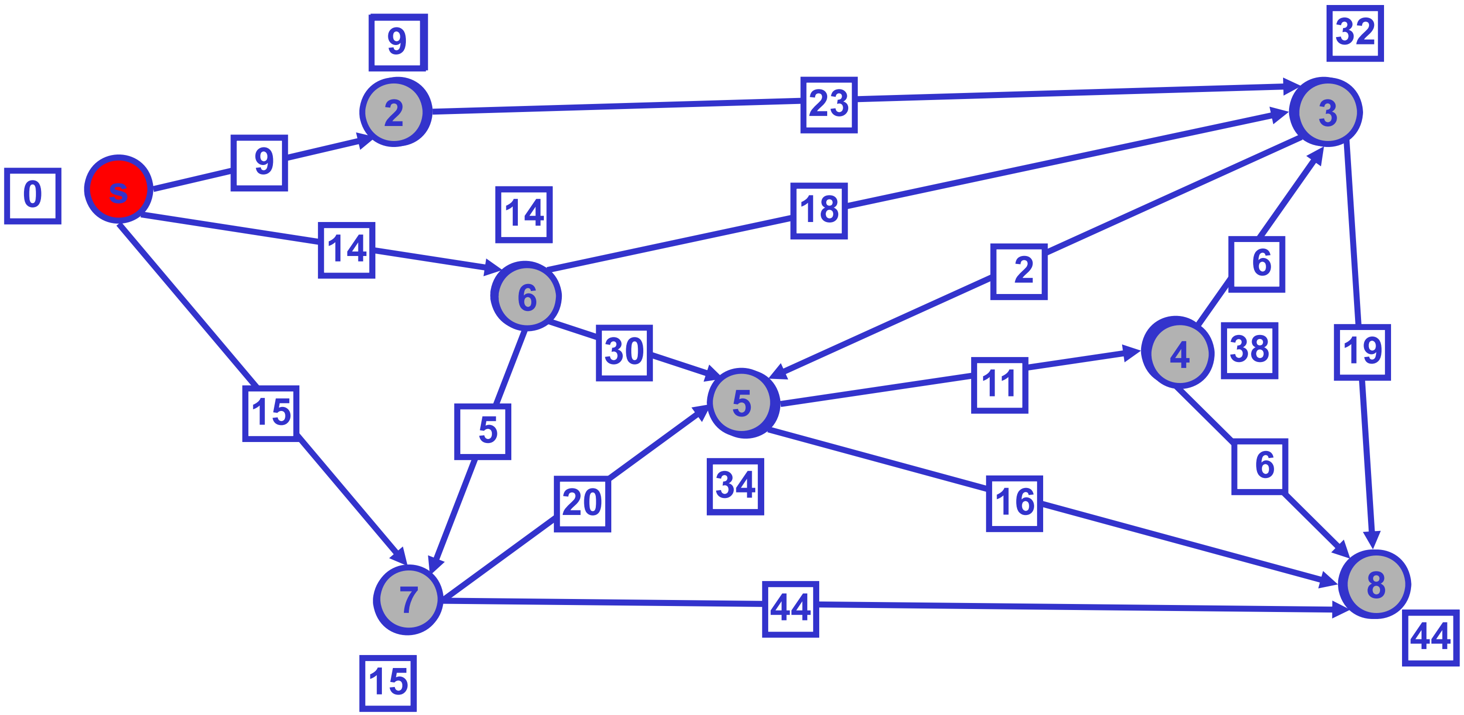
Dijkstra's Algorithm

- Let
  - **N** denotes the set of nodes in the graph
  - **s** denotes the node for which compute paths
  - $\mathbf{w_{ij}}$ denotes the non-negative cost (weight) for edge from the node i to the node j, ∞ if there is not an edge
  - $\mathbf{C_{sn}}$ denotes the cost of the path from the node s to the node n
  - $\mathbf{P_j}$ denotes the next hop from the node s toward the node j
- Then the algorithm is defined as follows

```
∀ n є N   /* initialization */
    if n ≠ s
        C_sn = ∞
    else
        C_sn = 0

while not empty(N)
    c = argmin (C_sn : n є N)
    N = N – {c}
    ∀ n є N
        if C_sn > C_sc + w_cn then
            C_sn = C_sc + w_cn
            P_n = c
```

Dijkstra's Algorithm



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Link-State Pros & Cons

- Link State main features are
  - Fast convergence
  - Nodes have topology information
  - Small quantity of packet exchanged
  - Good scalability (complexity is $O(E \cdot \log N)$)

- But the problems are
  - Amount of information stored at each node is large
  - Not suitable for broadcasting networks
  - Oscillations are possible when changes are frequent

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Distance Vector Vs. Link State

- Message complexity
  - DV exchange messages between neighbors
  - LS with N nodes and E links, O(NE) messages sent
- Speed of Convergence
  - DV
    - May be routing loops
    - Count-to-infinity problem
    - Convergence time varies
  - LS
    - Requires O(NE) messages
    - May have oscillations
- Robustness: what happens if router malfunctions?
  - DV
    - Nodes can advertise incorrect path cost
    - Each node’s table used by others
    - Error propagate into the network
  - LS
    - Nodes can advertise incorrect link cost
    - Each node computes only its own table

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Implement Routing for the Global Network

- Scale with 50 million destinations
  - It is not possible to store all the destinations in routing tables
  - Routing table exchange would swamp links
- Administrative autonomy
  - The global network (internet) is a network of networks
  - Each network admin may want to control routing in its own network

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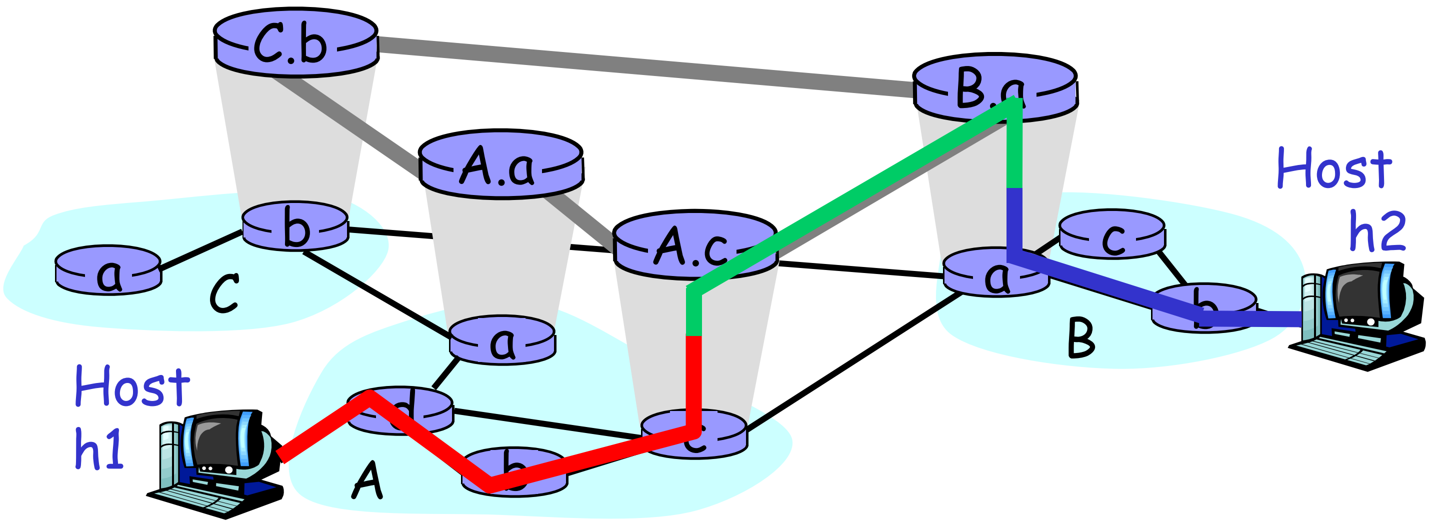
Hierarchical Routing

- Routers are aggregated into regions called, "autonomous systems" (AS)
- Routers in same AS run same routing protocol "intra-AS" routing protocol
- Routers in different AS can run different "intra-AS" routing protocol
- Gateway routers are special routers in AS
  - Run intra-AS routing protocol with all other routers in AS
  - Are also responsible for routing to destinations outside AS running inter-AS routing protocol with other gateway routers

Hierarchical Routing



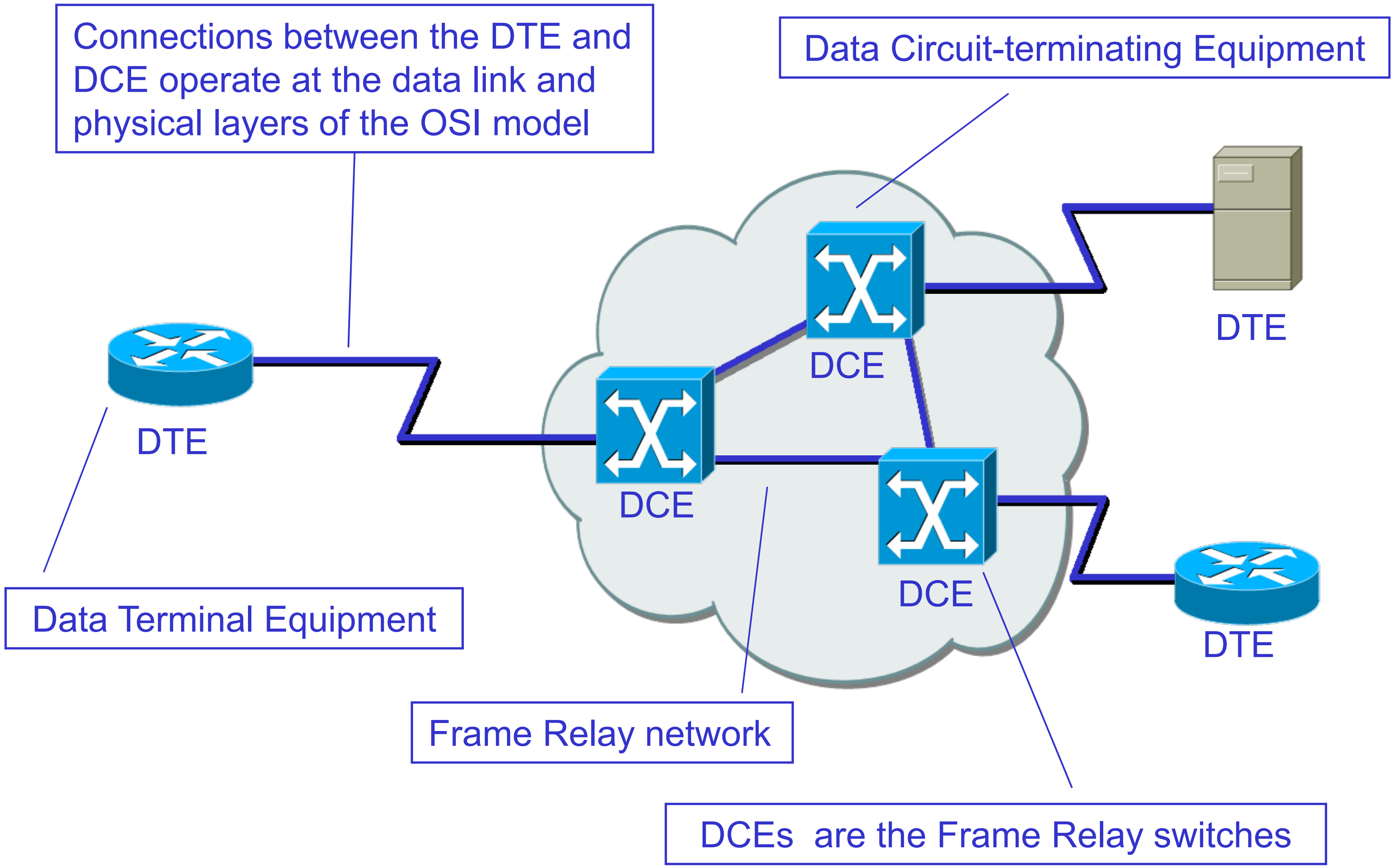
WAN Technologies

- In the past
  - Arpanet
  - X.25
- Currently
  - Frame Relay
  - Asynchronous Transfer Mode (ATM)
  - Synchronous Digital Hierarchy (SDH)

Frame Relay

- Connection-oriented technology for economic transmission of data with acceptable speed
- Mostly used for permanent virtual connections for which signaling for the connection establishment is not necessary
- Does not provide flow or error control
  - They must be provided by the upper-layer protocols
- Primary competitive advantage is its low cost
- Operates up to 45 Mbps with 56 kbps and 384 kbps being the most popular

Frame Relay Infrastructure



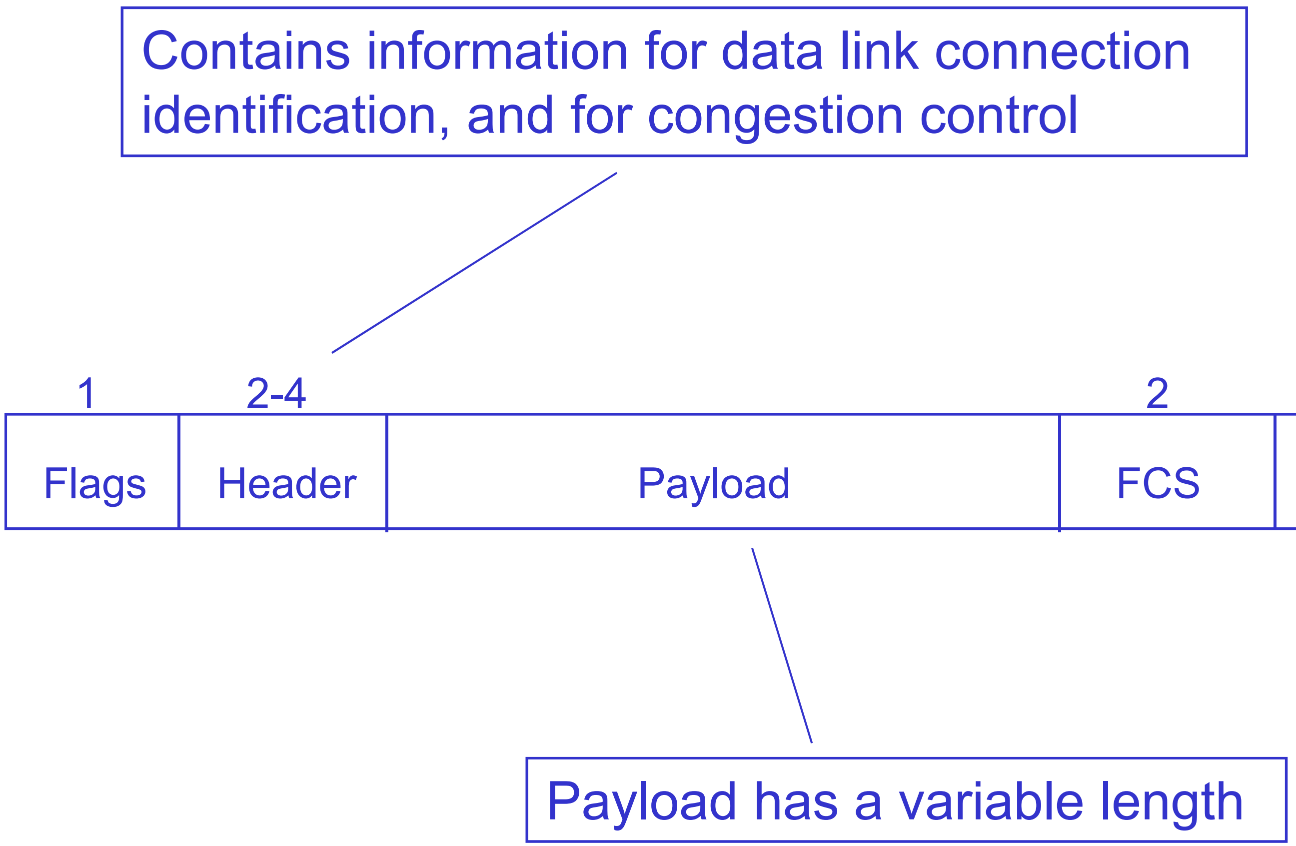
Frame Relay Devices

- Data Terminal Equipment (DTE)
  - DTEs generally are considered to be terminating equipment for a specific network and typically are located on the premises of a customer
  - Example of DTE devices are terminals, personal computers, routers, and bridges
- Data Circuit-terminating Equipment (DCE)
  - DCEs are carrier-owned internetworking devices
  - The purpose of DCE equipments is to provide clocking and switching services in a network, which are the devices that actually transmit data through the WAN

Frame Relay Packet Switching

- Frame Relay operates over a permanent virtual circuit, which means that a permanent connection exists between the source DCE and destination DCE over the frame relay network
  - Therefore, there is no need for call setup and termination
- Frame Relay has two states:
  - Data transfer: between the DCE and the provider's DTE
  - Idle: the line is active, but no data is being transferred

Frame Relay Packet

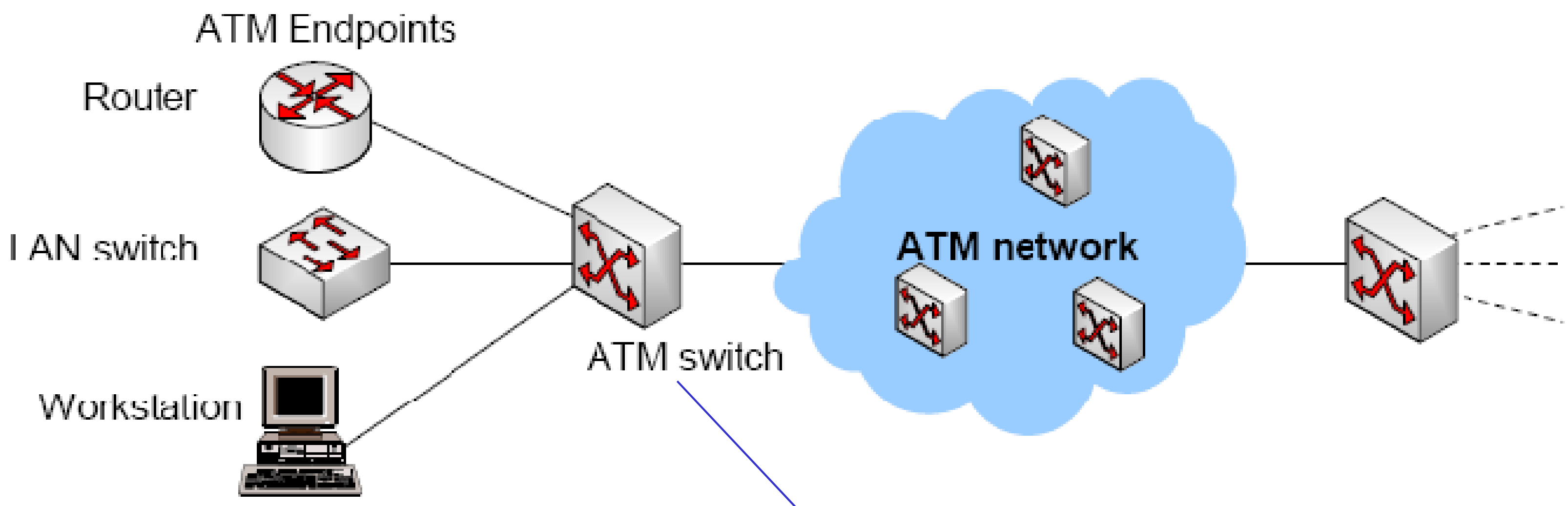


ATM

- Acronym of Asynchronous Transfer Mode
- Was designed by telephone companies for use in wide area networks, but is often used in local area networks
- Intended to accommodate voice, video and data
- Performance guaranteed (statistical)
  - Connection oriented interface
  - Packet forwarding performed by hardware
- Operates up to 622 Mbps

ATM Infrastructure

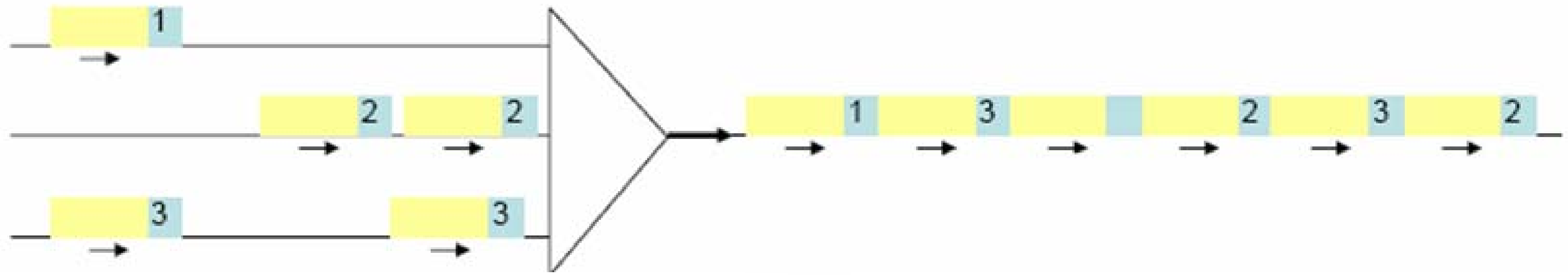
Contains an ATM network interface adapter to connect different networks with the ATM network



Builds the network infrastructure and can be connected with other ATM switches

ATM Packet Switching

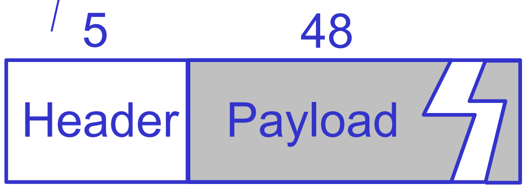
- Packet switching is like time division multiplexing, but without reserved time slots



- Asynchronous time multiplexing of several virtual connections
- Continuous cell stream
- Unused cells are sent empty
- Within overload situations, cells are discarded

ATM Cell

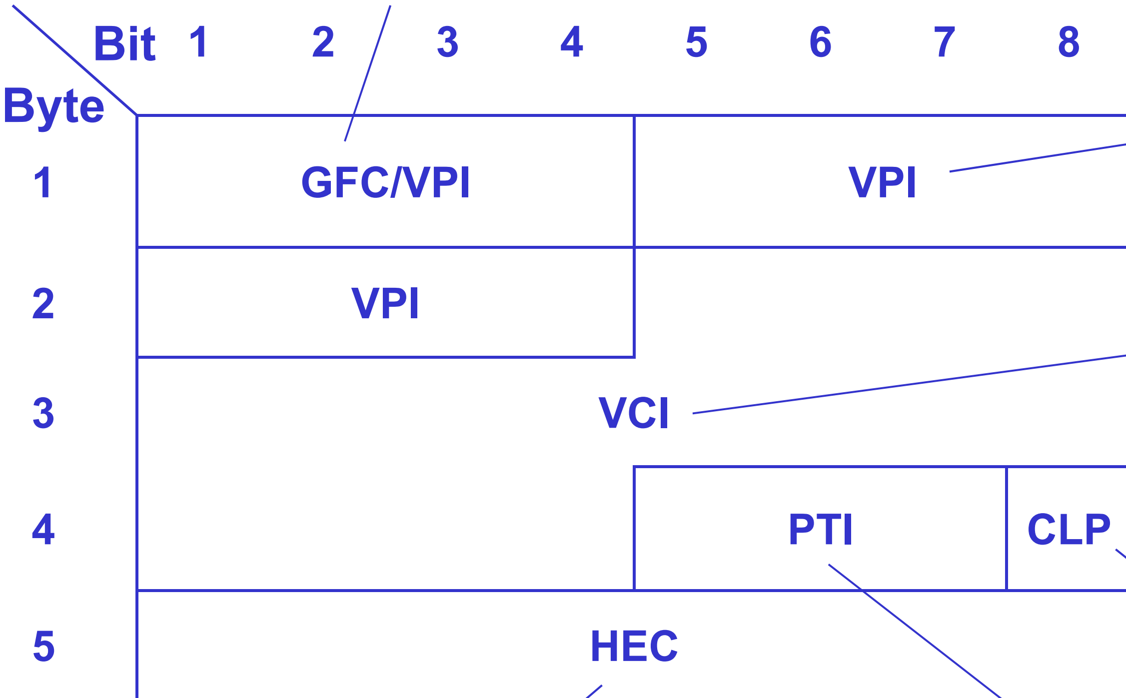
Network-Network Interface (NNI) header for communication between two switches



User-Network Interface (UNI) header for communication between switches and endpoints

Cell Header

Generic Flow Control: used only with UNI, for local control of the transmission of data into the network. With NNI these bits are used to increase the VPI field



Virtual Path Identifier: identifies the path to the destination

Virtual Channel Identifier: identifies the channel towards the destination

Cell Loss Priority: If the bit is 1, the cell can be discarded within overload situations

Header Error Control: CRC for the first 4 bytes; single bit errors can be corrected

Payload Type Identifier: describes content of the data part

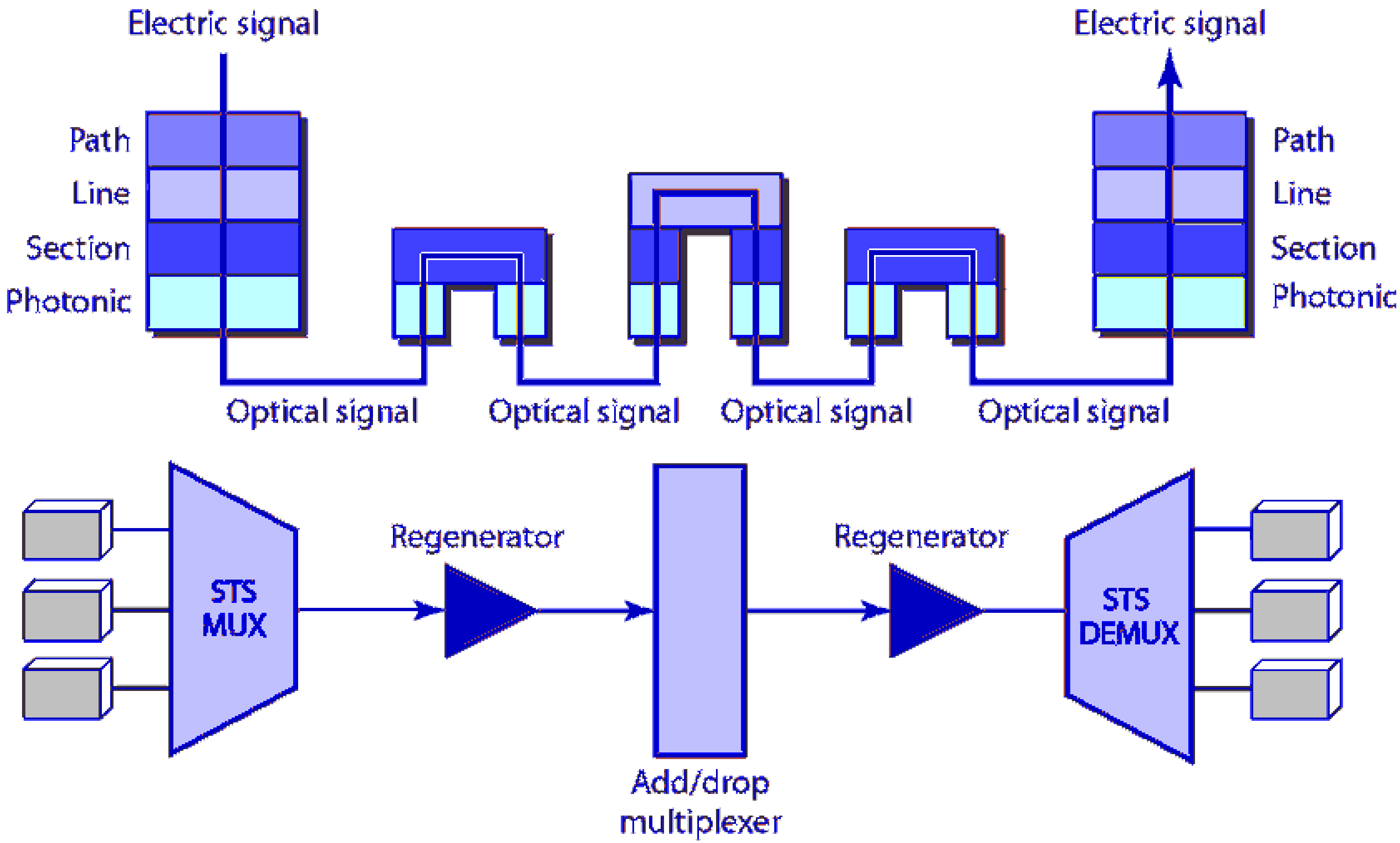
Integration of ATM into Existing Networks

- ATM offers an interface to higher layers similar to TCP in the Internet protocols
- ATM had problems during its introduction:
  - Very few applications which build directly upon ATM
  - In the interworking of networks, TCP/IP was standard
    - Without TCP/IP binding, ATM could not be sold!
- Therefore different solutions for ATM were defined
  - IP over ATM
  - LAN emulation

SDH

- Acronym of Synchronous Digital Hierarchy
- Defines a set of physical layer standards for communications over optical fiber
- May have point-to-point, ring and mesh topology
- Operates up to 10 Gbps
- Is used in Europe and Japan, but an equivalent technology, called Synchronous Optical Network (SONET), is used in North America

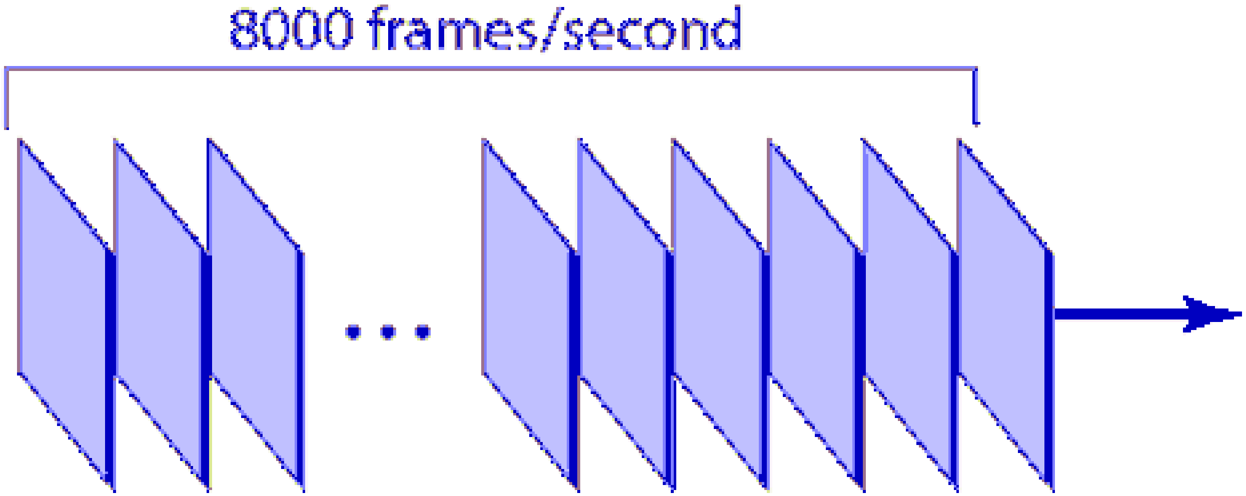
SDH Infrastructure

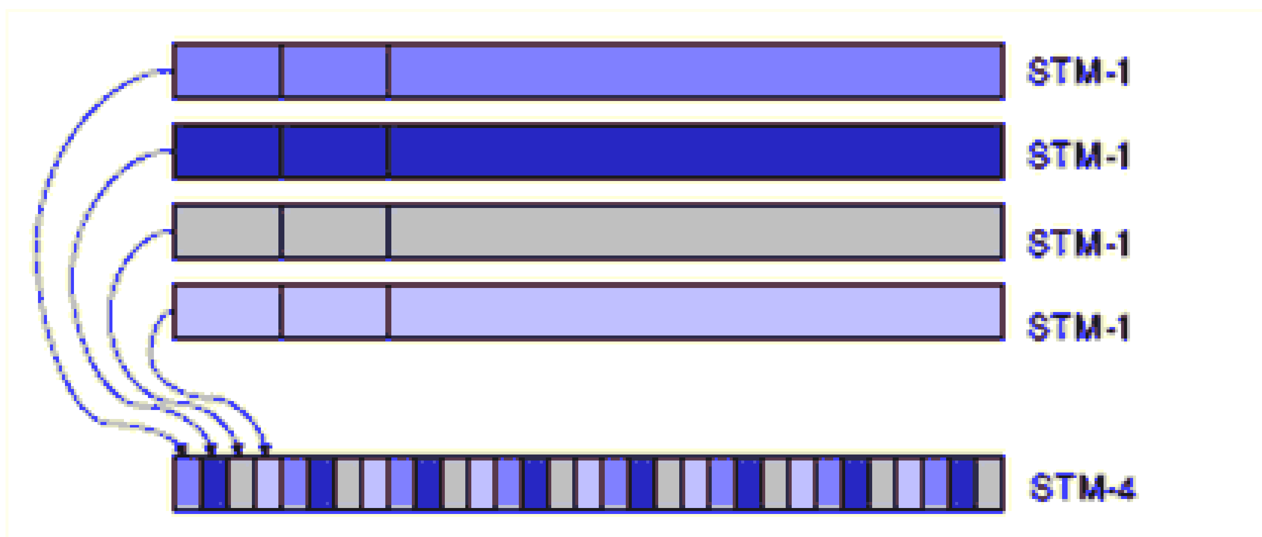


SDH Packet Switching

- The transmission is organized into a continuous sequence of packets
- Each packet contains a fixed number of time slots
- Each time slot is pre-assigned to a specific input link
- If the buffer of an input link has no data, then its associated time slot is transmitted empty
- A time slot dedicated to an input link repeats continuously packet after packet, thus forming a channel or a trunk

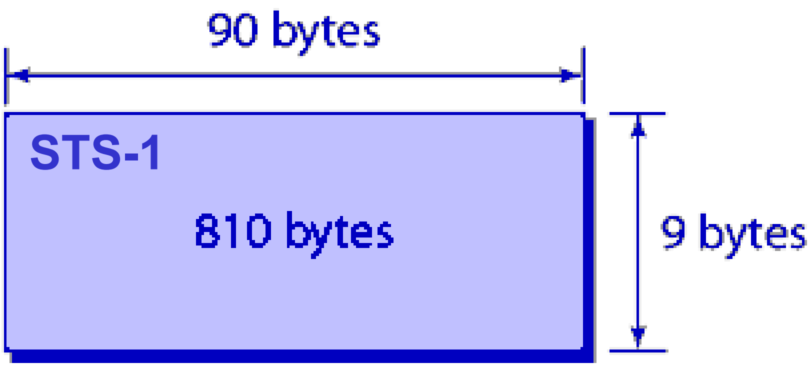
SDH Packet Switching





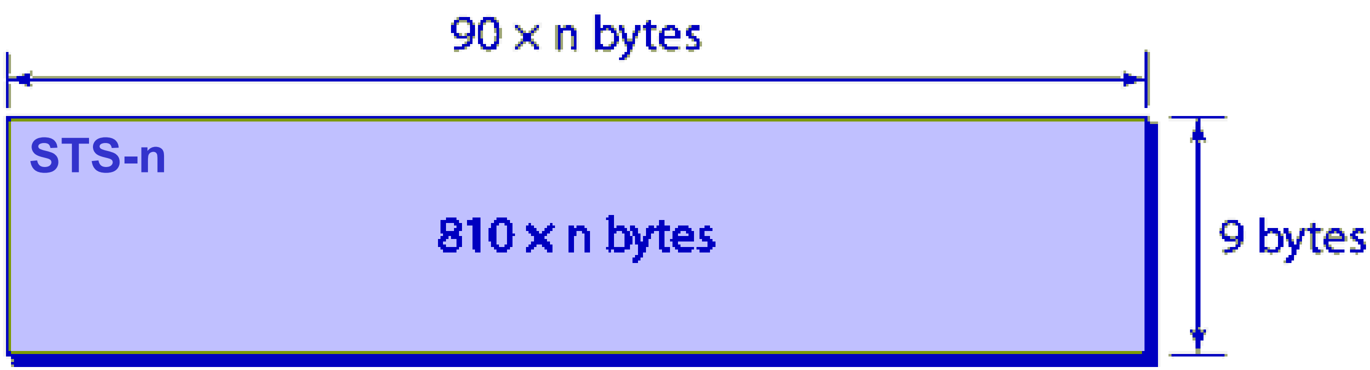
SDH STS

STS is the acronym of Synchronous Transfer Signal



An STS frame contains section, line and path headers and data

STS-1 speed is 810 x 8 x 8000 = 51,84 Mbps



STS-n speed is n x 51,85 Mbps