Computer Networks

Introduction

Kapitel

1. **Introduction**
   - **Computer networks**
   - **Classification**
   - **Multiplexing**
   - **Standardization**
2. Protocols
3. Application layer
4. Web services
5. Distributed hash tables
6. Time synchronization
7. Transport layer
8. UDP and TCP
9. TCP performance
10. Network layer
11. Internet protocol
12. Data link layer

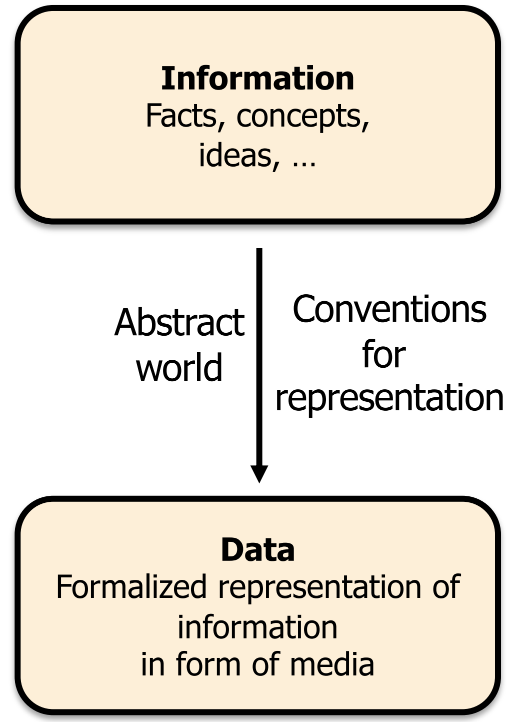
Top-Down-Approach

Application Layer
Presentation Layer
Session Layer
Transport Layer
Network Layer
Data link Layer
Physical Layer

Introduction

What to Communicate: Information, Data

- Information
  - Facts, concepts, ideas
  - A human-oriented term
- **Data** (encapsulated in media)
  - A formalized representation of facts, concepts, ideas
  - Example: text, speech, picture, video
  - A human interpretation of data, conferring meaning to data
- Note:
  - Only data can be communicated,
  - The recipient of data restores information,
  - The recipient interprets data – subject to her interpretation



The Data Tsunami

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- In 2000 years of recorded history humans created 2 Exabytes of data.
- We generate over 2.5 Exabytes of data/day now!
  - Different sources
- Problem: extracting information out of **data**
  - Where to process them?
  - Bringing data to the processing?
  - Processing data where it emerges and transport (partial) results?

Value	Metric	
1000	kB	kilobyte
1000^2	MB	megabyte
1000^3	GB	gigabyte
1000^4	TB	terabyte
1000^5	PB	petabyte
1000^6	EB	exabyte
1000^7	ZB	zettabyte
1000^8	YB	yottabyte

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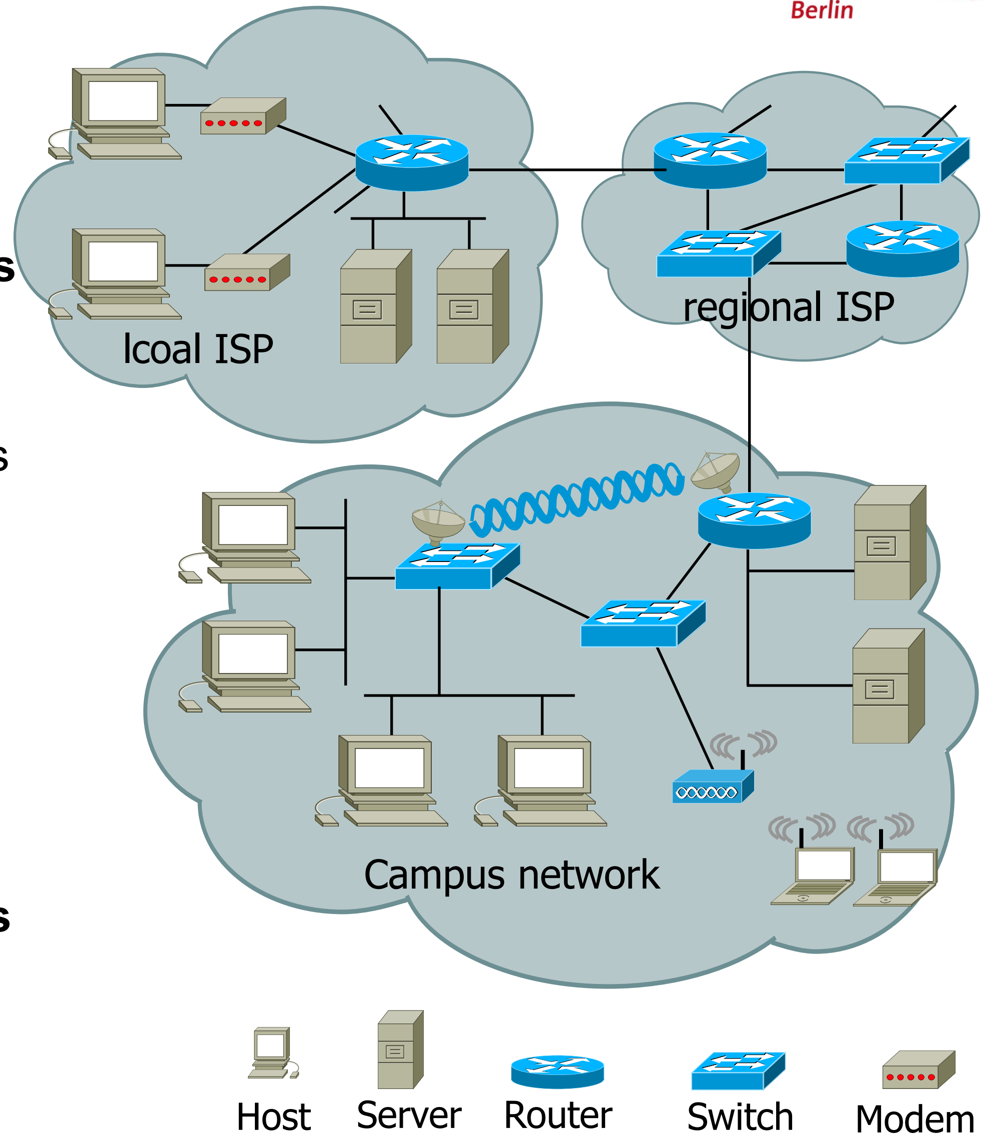
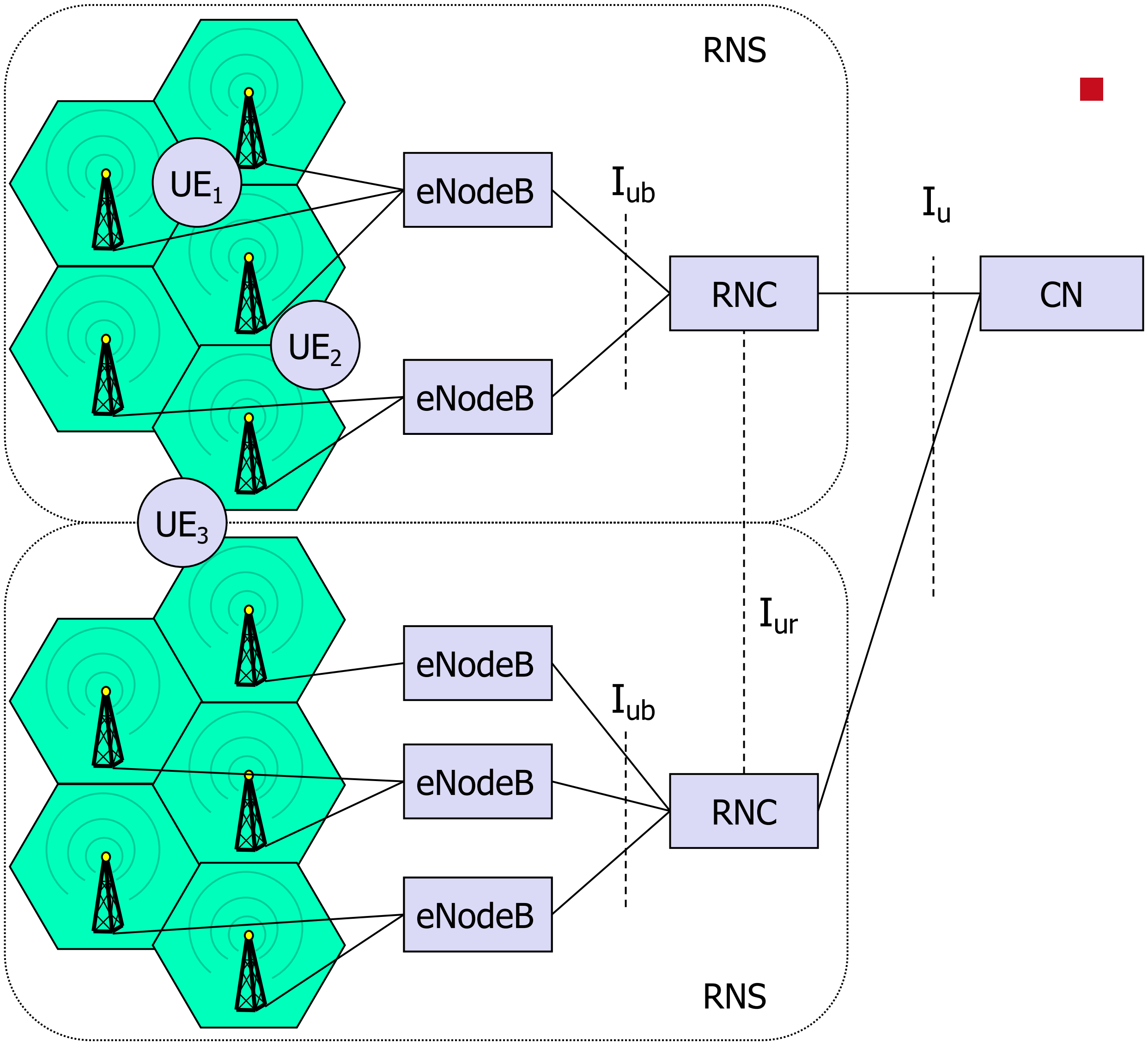
Examples of computer networks

- Internet
  - Communication between **Applications** on **End Systems** (**Host**, **Server**)
  - Use of **Internet Protocols** (e.g., TCP, UDP, IP) and others (e.g., Ethernet, WLAN)
  - Infrastructure consists of **Switches** and **Routers**, also RF base stations and modems
  - Wired and wireless **Connections**
  - Differentiation between **access network** and **core network**
  - Internet Service Provider (ISP)



Examples of computer networks



- Cellular networks
  - mobile telecommunications: voice and data
  - Mobile station (User Equipment)
  - Radio Network Subsystem for RF-based cellular networts and base stations (eNodeB / gNodeB)
  - Access network, core network for signaling, transport, connection to other networks

Examples of computer networks

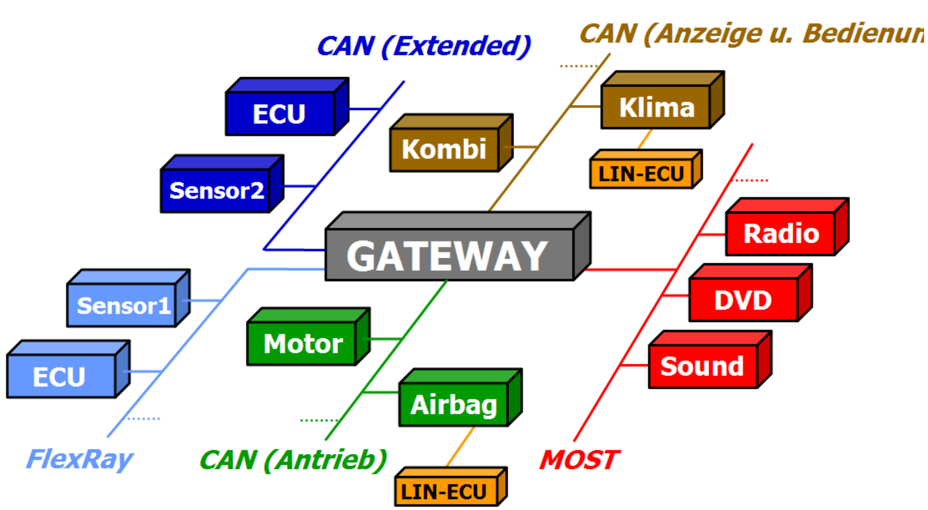
- Ad Hoc Networks, Sensor Networks
  - Ad Hoc Networks: no infrastructure, duality between end systems and routers, self-organizing

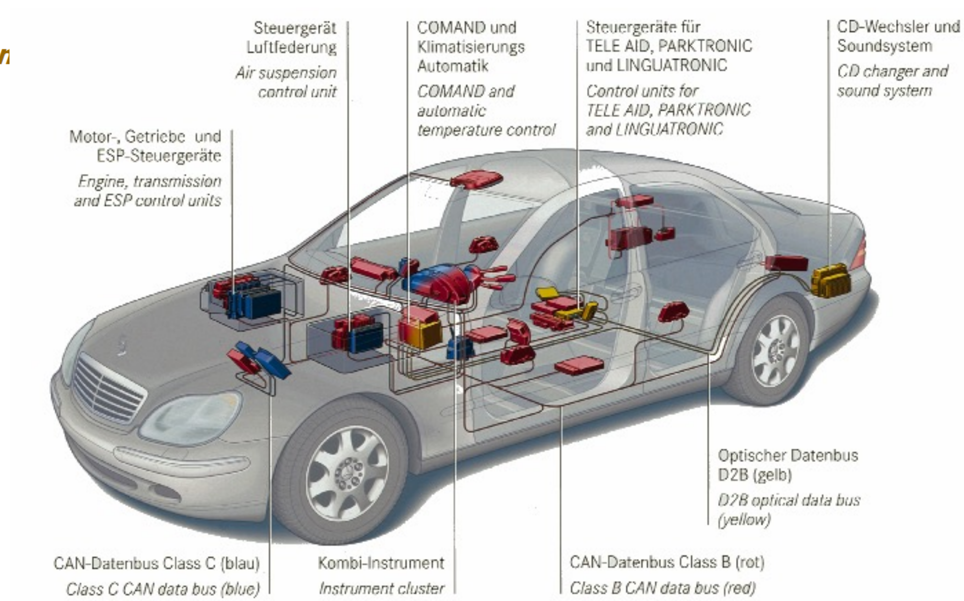
  - Wireless Sensor Networks (WSN), modern IoT
    - Small and simple components
      - Small (cm2, mm2), cheap
      - Limited energy (battery or energy harvesting)
      - Micro controller-based
      - Wireless communication
      - Sensors such as light, humidity, pressure, acceleration, …

    - Application in logistics, farming, health care, home automation…

Examples of computer networks

- In-car communication networks
  - Mid-size cars have 60-100 electronic control units (ECU) for engine control, driver assistance, comfort, infotainment
  - Bus systems like Controller Area Network (CAN)
  - Strict requirements on robustness and real-time capabilities

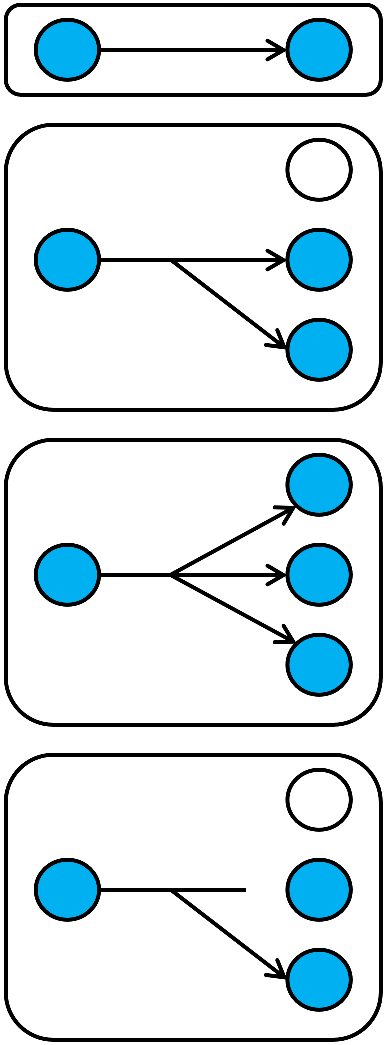




Classification of communication networks

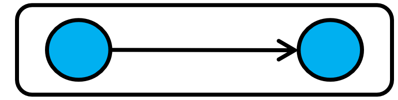
Classification of communication networks

- Communication partners
  - **Unicast** (point-to-point): one sender, one receiver
  - **Multicast** (;point-to-multipoint): one sender, a group of receivers
  - **Broadcast** (to everybody): message to all nodes in the network
  - **Anycast** (to somebody): message to one receiver out of a group of potential targets



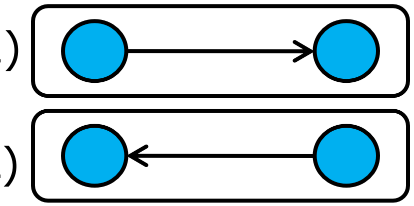
Classification of communication networks

- Direction of communication
  - **simplex**: unidirectional connection

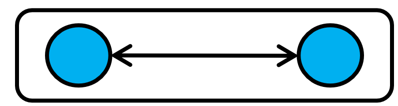


  - **half-duplex**: bidirectional connection but only simplex per time

(1)
(2)



  - **(full-)duplex**: bidirectional at the same time



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Classification of communication networks

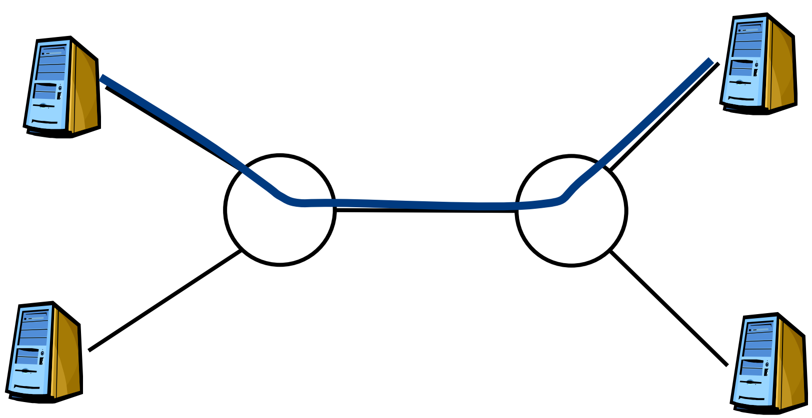
- Communication medium
  - **wired**
    - e.g., copper cables or fiber optics
    - Bit rates of kbps to Gbps
    - Signal propagation speed close to speed of light (depending on medium)
      $c \approx 2 \cdot 10^8$ m/s = 200 m/µs
    - Low bit error rates, e.g., 10^{-10} on fiber optics
  - **wireless**
    - e.g., RF (radio frequency) or infrared
    - Bit error rates rather high (many signal propagation issues): 10^{-5} to 10^{-2}
    - Bit errors often appear in bursts

Classification of communication networks

- Switching mode
  - **Circuit Switching**
    - Connection is established between sender and receiver using a **signaling protocol** (e.g., time or frequency multiplexing)
    - Available bit rate needs to be shared among all connections
    - Standard for classic telephony, inefficient for bursty data communication
  - **Packet Switching**
    - Data is being sent in form of packets from sender to receiver
    - Sharing of bit rate more efficient
    - Temporary busts can be dealt with using buffers
    - This may lead to artificial delays and even buffer overflow

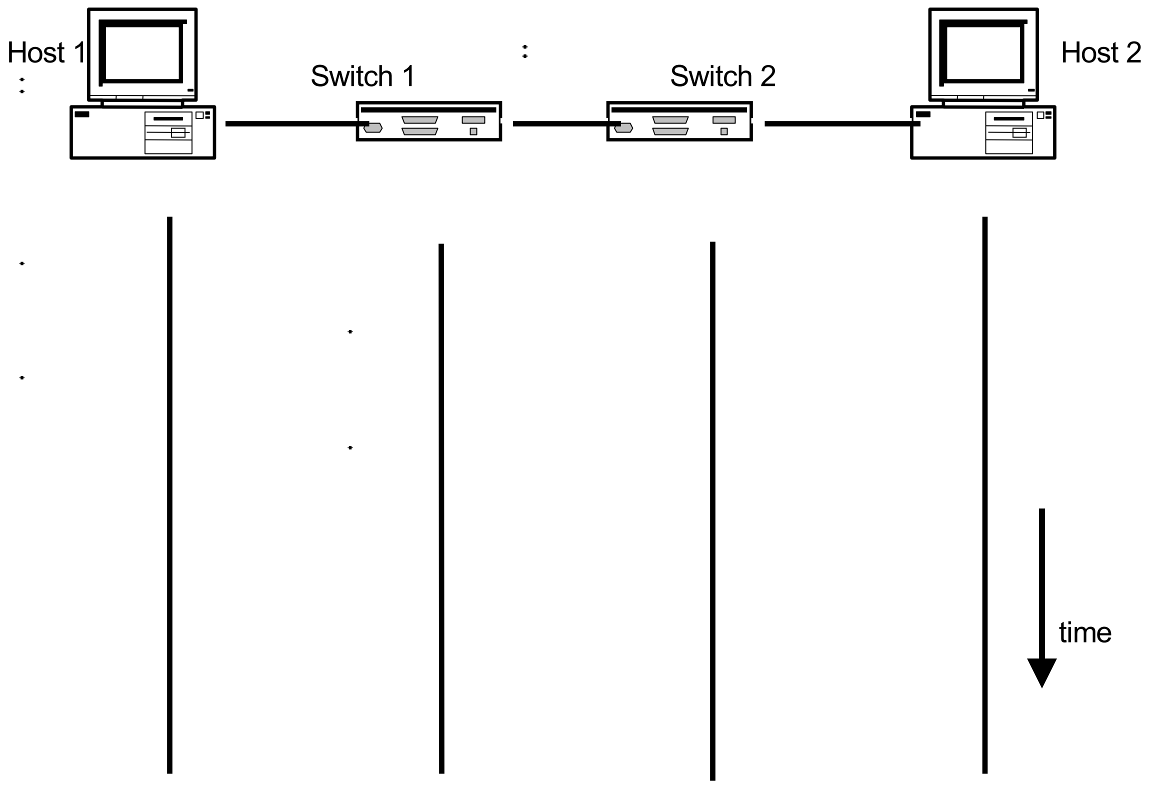
Option 1: Circuit Switching

- Circuit switching: the switching elements configure, on demand, a “path” between terminals.
  - Determines really the route (cmp. “Fräulein vom Amt”) and resources!
  - The circuit lasts for duration of communication

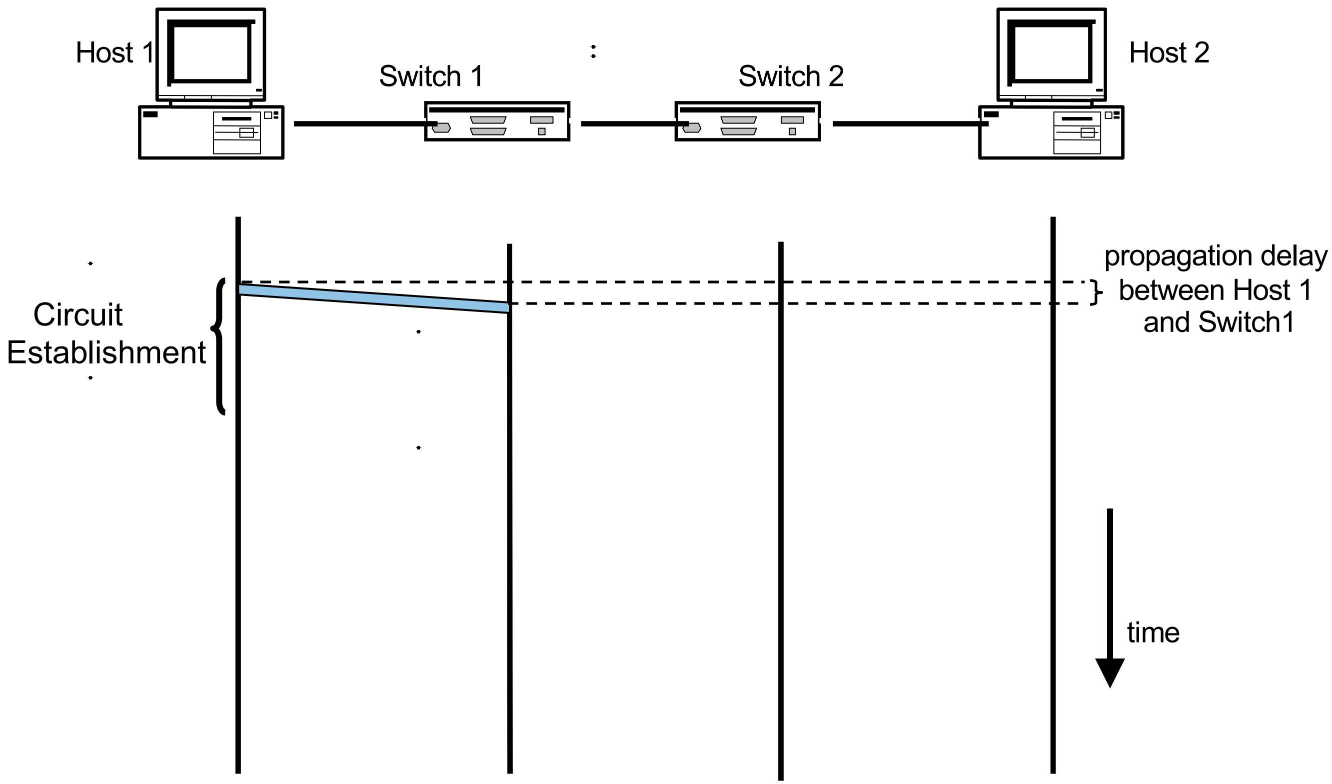


Source: wikipedia

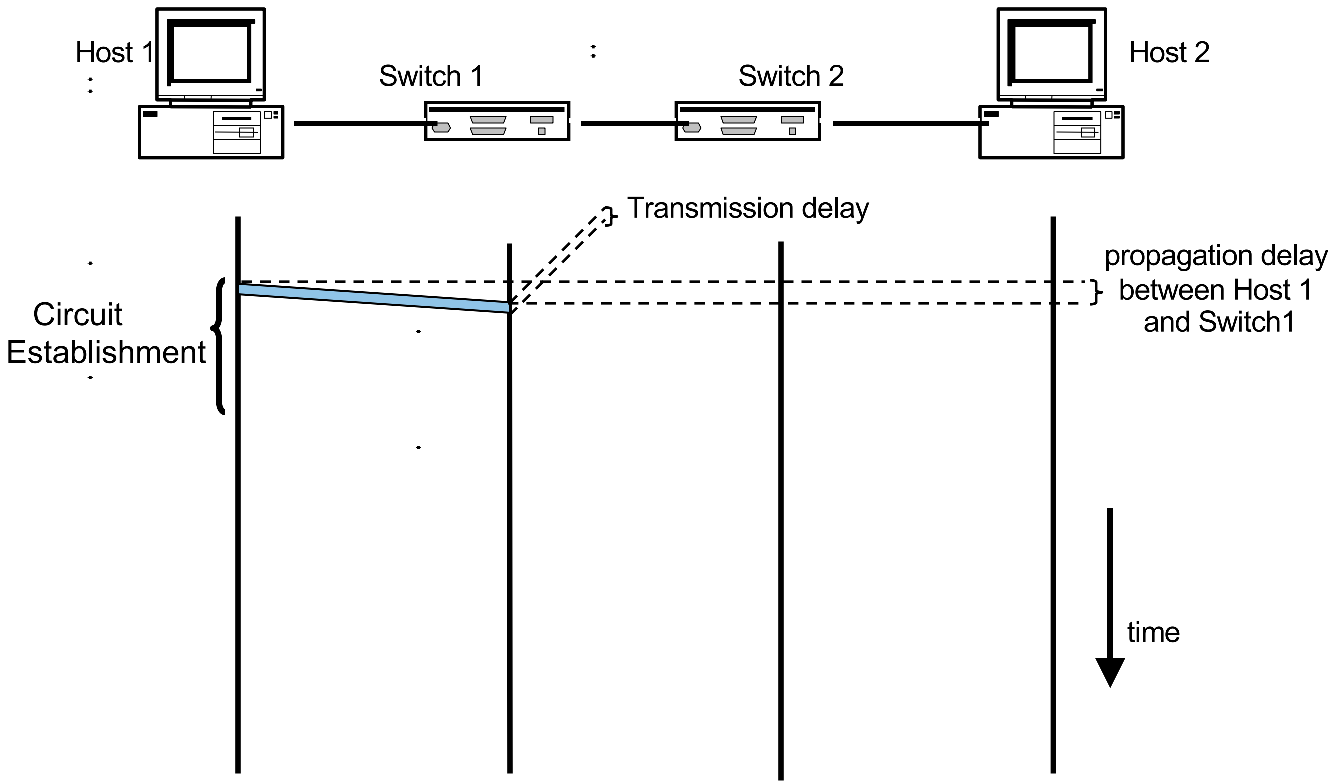
Timing in Circuit Switching (1)



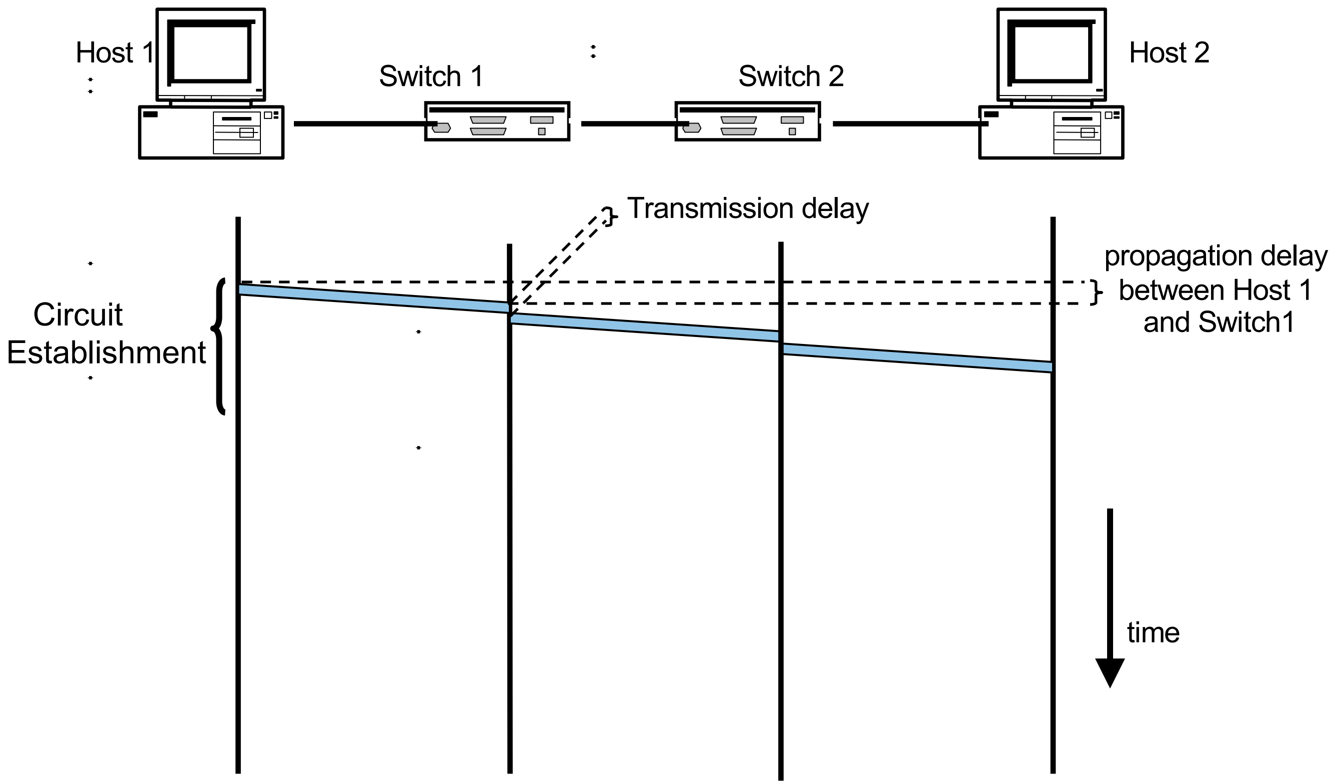
Timing in Circuit Switching (2)



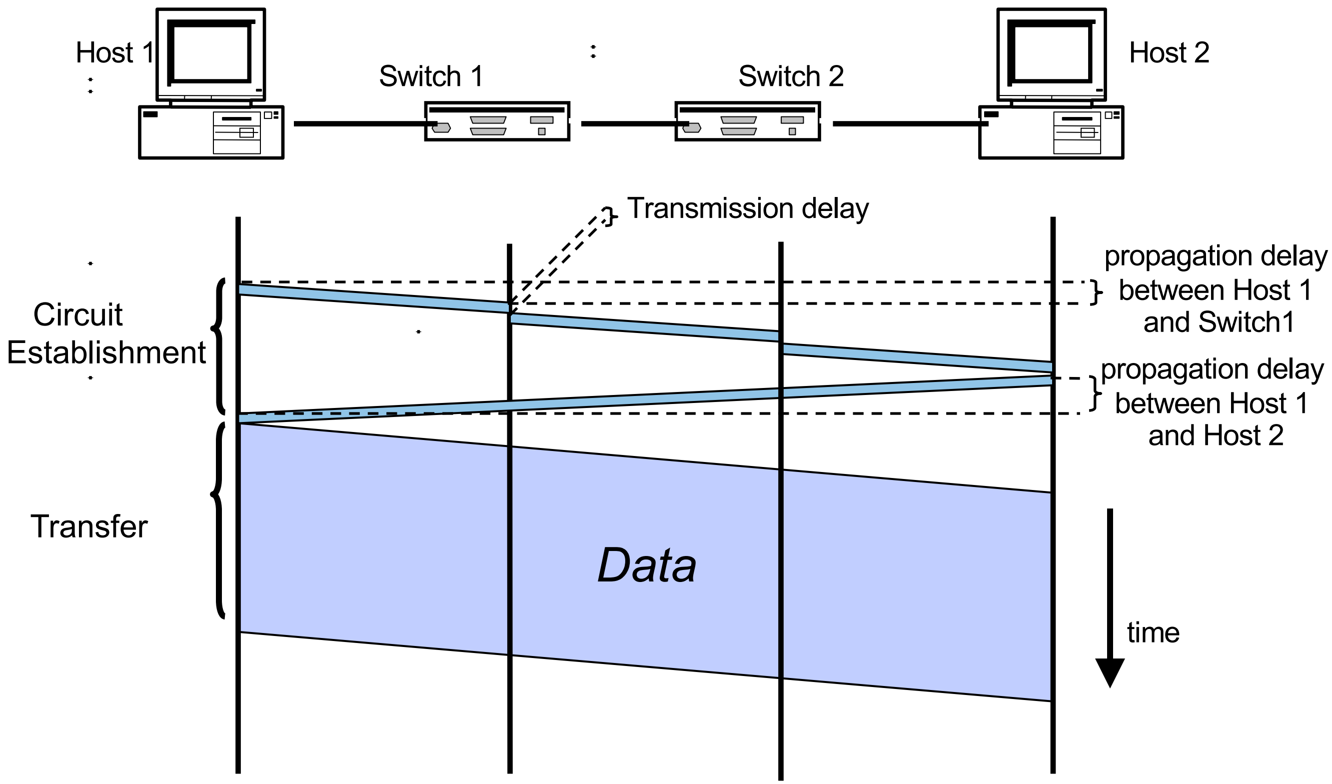
Timing in Circuit Switching (3)



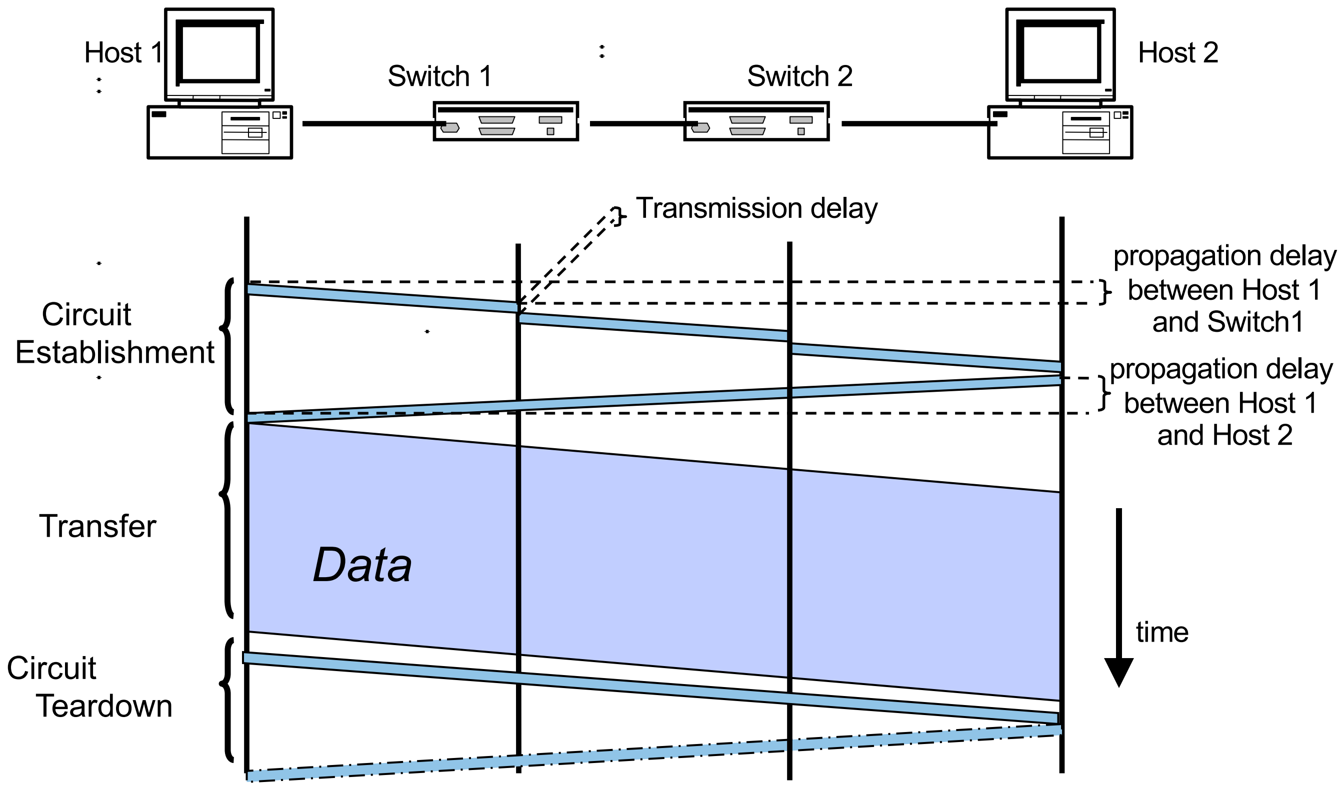
Timing in Circuit Switching (4)



Timing in Circuit Switching (5)



Timing in Circuit Switching (6)

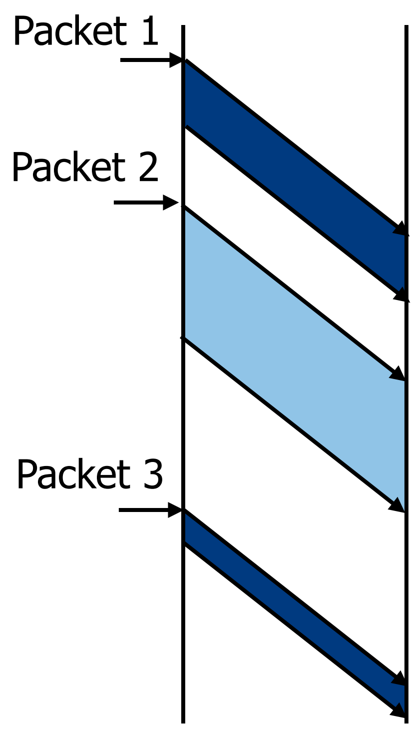


Circuit switching – Evaluation

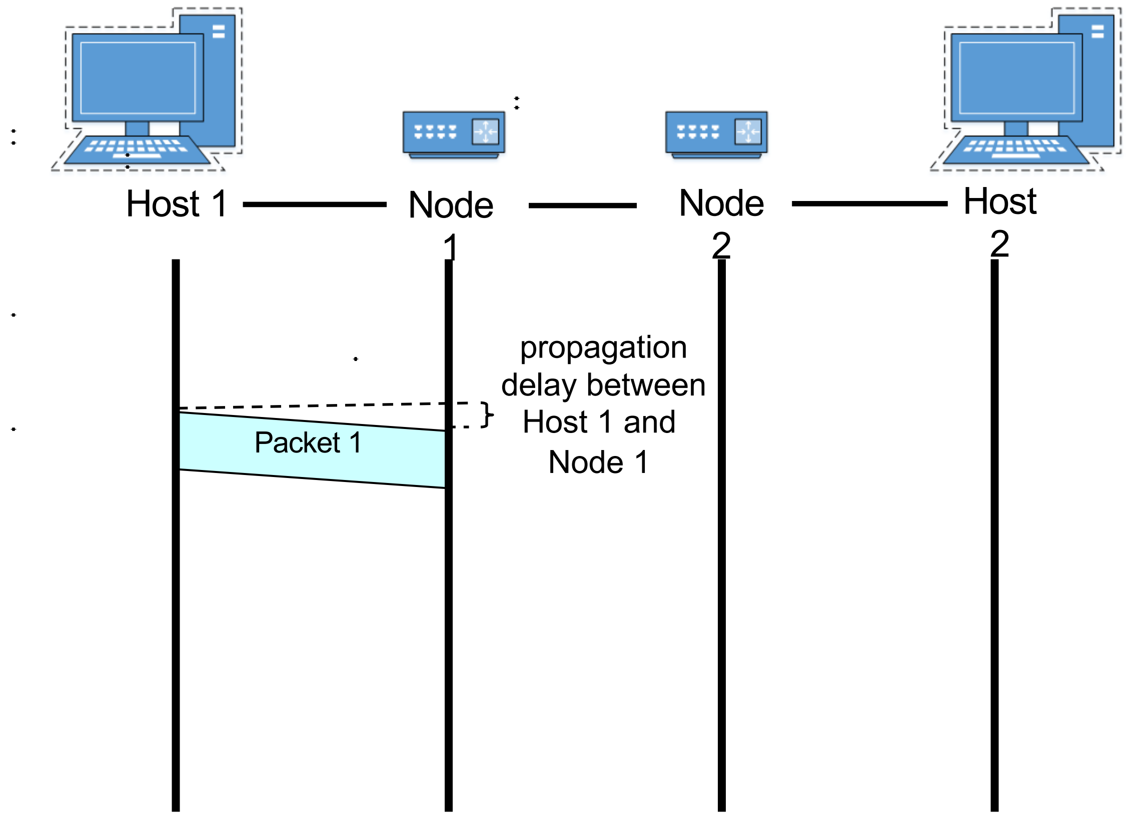
- Advantages
  - Once circuit is established, the resources are guaranteed to participating terminals,
  - Once circuit is established, data has only to follow the circuit (forwarding is very simple)
- Disadvantages
  - The need to establish the circuit upfront delays the begin of data transmission,
  - Resources are dedicated – what if there is a pause in the communication?
  - The route is fixed – what if one of the switches breaks down?

Option 2: (Datagram) Packet Switching

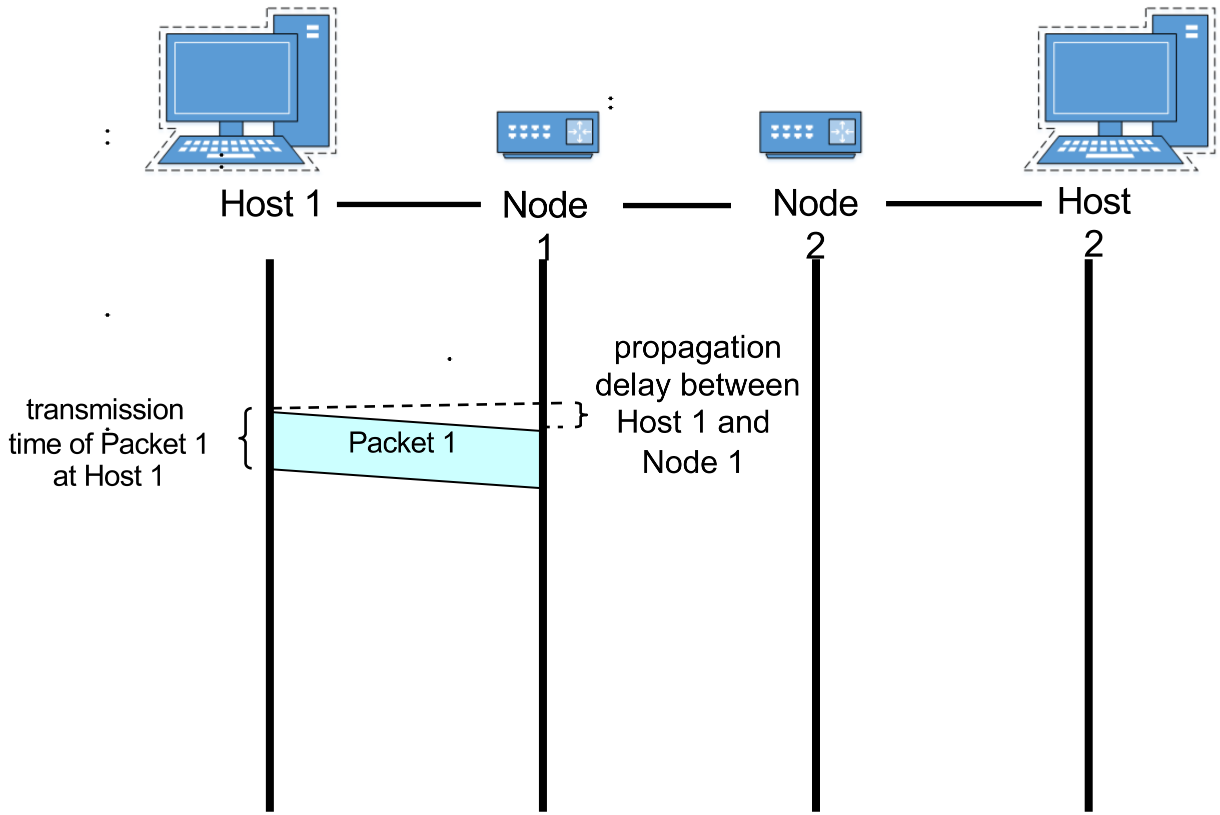
- Chunk data into packets
  - Packets contain some actual data that is to be delivered to the recipient (can have different, but bounded size),
  - Also need administrative information, e.g., who is the recipient,
  - Sender sends out a packet occasionally, instead of a continuous flow of data
- Problems: How to detect start and end of a packet, which information to put into a packet, …
- Higher per packet processing cost in each switch …



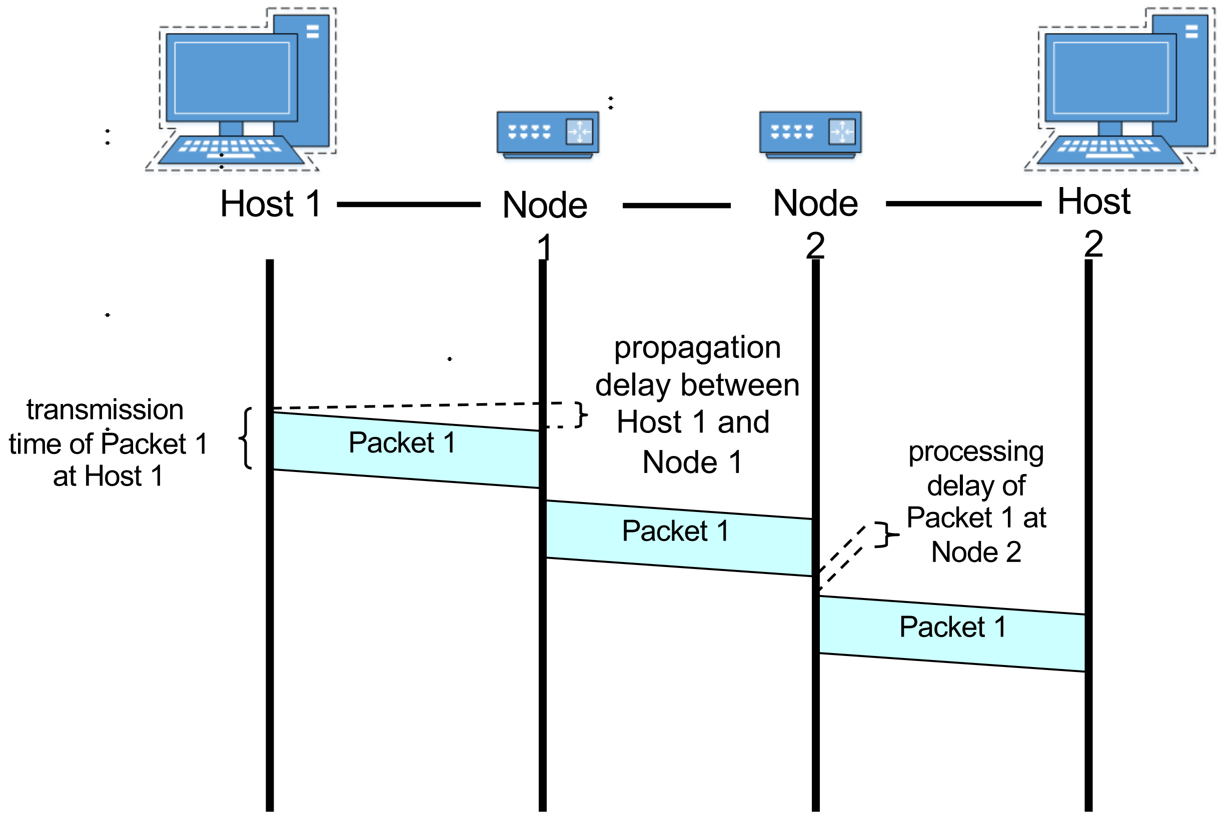
Timing of Datagram Packet Switching (1)



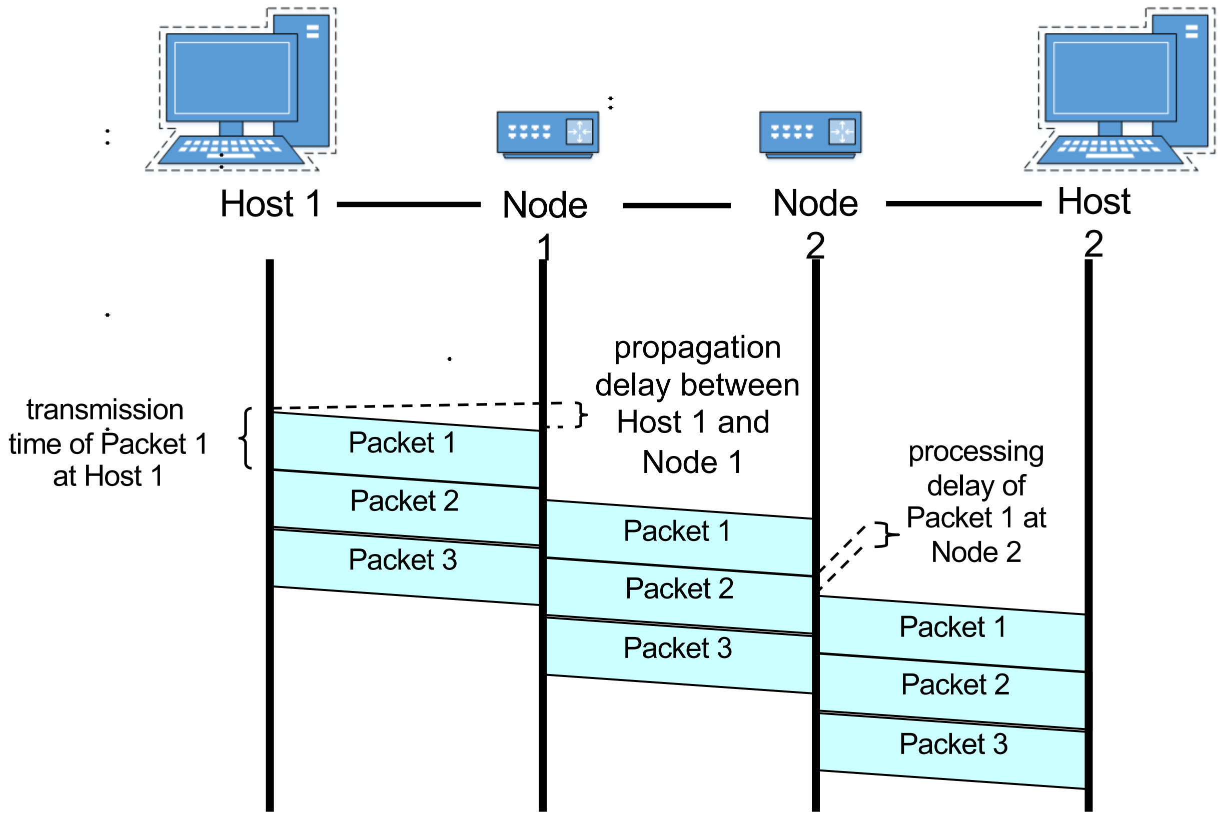
Timing of Datagram Packet Switching (2)



Timing of Datagram Packet Switching (3)



Timing of Datagram Packet Switching (4)

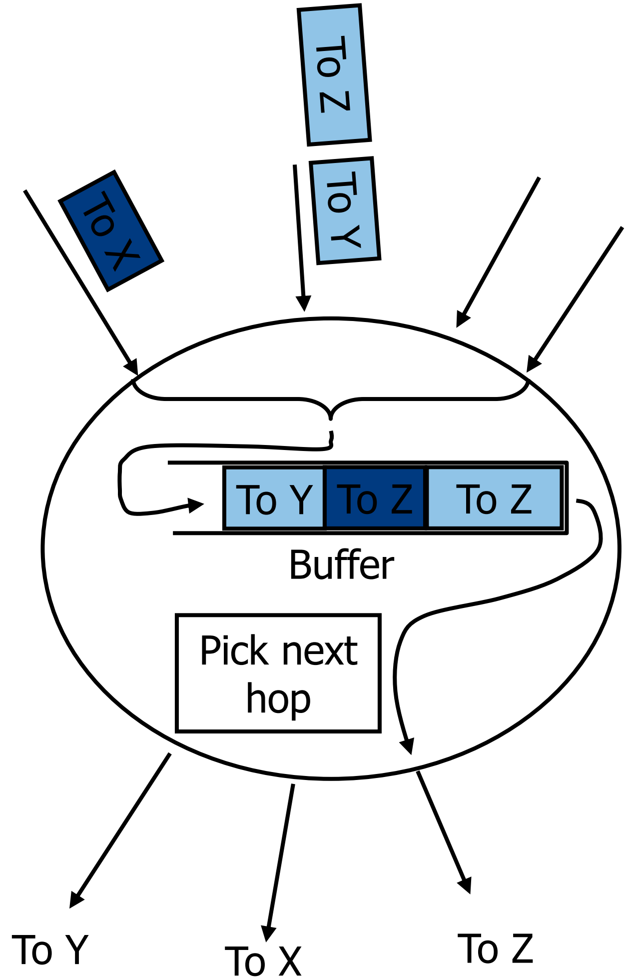


Comparison

Item	Circuit switched	Packet switched
Call setup	Required	Not needed
Dedicated physical path	Yes	No
Each packet follows the same route	Yes	No
Packets arrive in order	Yes	No
Is a switch crash fatal	Yes	No
Bandwidth available	Fixed	Dynamic
Time of possible congestion	At setup time	On every packet
Potentially wasted bandwidth	Yes	No
Store-and-forward transmission	No	Yes
Transparency	Yes	No
Charging	Per minute	Per packet

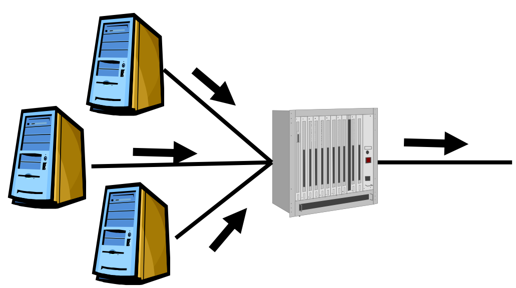
Packet Switches

- Switches take on additional tasks
  - Receive a complete packet
  - Store the packet in a buffer
  - Find out the packet's destination
  - Decide where the packet should be sent next to reach its destination
    - Information about the network graph necessary
  - Forward the packet to this next hop of its journey
- Also called "store-and-forward" network



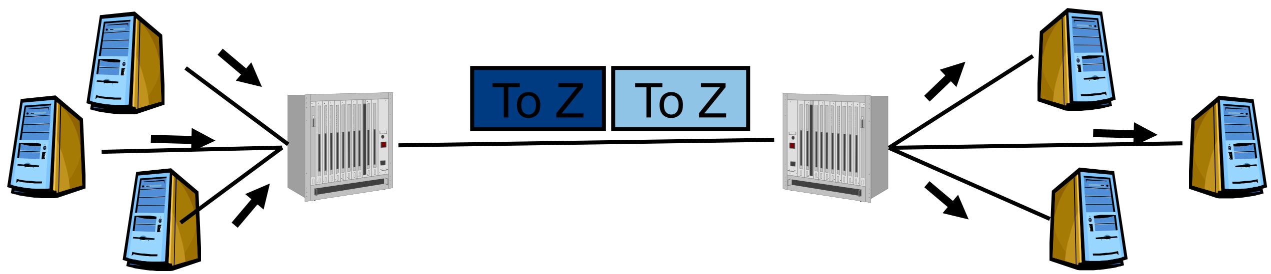
Multiplexing

- Previous example had two packets at the head of the queue destined for terminal Z
- Let us consider a switch with only a single outgoing line
  - Such a special case is called a multiplexer
  - Organizing the forwarding of packets over such a single, shared line is called multiplexing
  - Multiplexers in general need buffer space as well

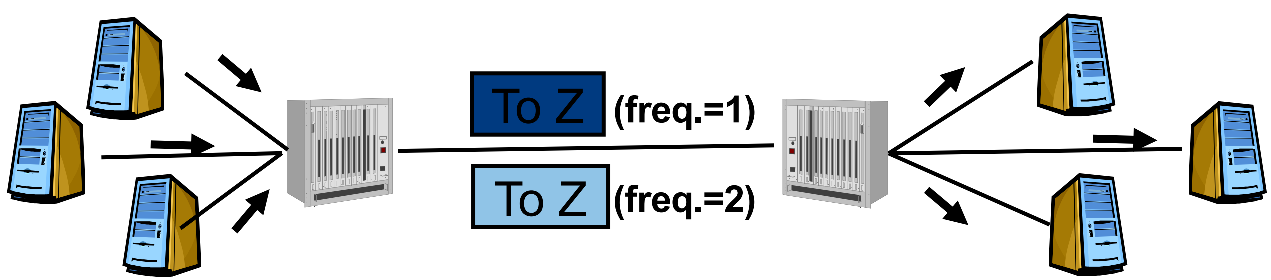


Multiplexing II

- Obvious option: Time Division Multiplexing (TDM)
  - Serve one packet after the other; divide the use of the connection in time



- Alternative: Frequency Division Multiplexing (FDM)
  - Use different frequencies to transmit several packets at the same time



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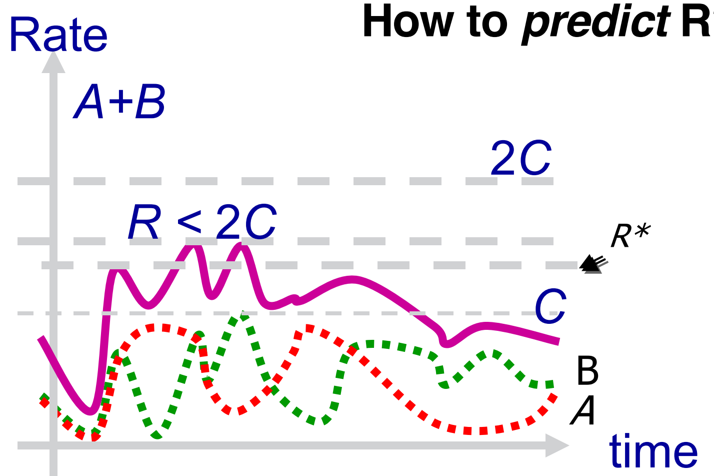
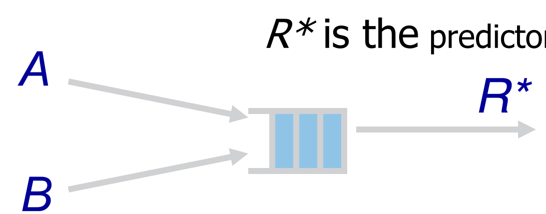
Statistical Multiplexing Gain

Statistical multiplexing uses at most R<2C.
How to *predict* R? There might be losses!





Statistical multiplexing gain (SMG) = $2C/R^*$

SMG: The ratio of rates that give rise to a particular queue occupancy, or particular loss probability.

It is hardly possible to account for maximum demand of numerous sources!

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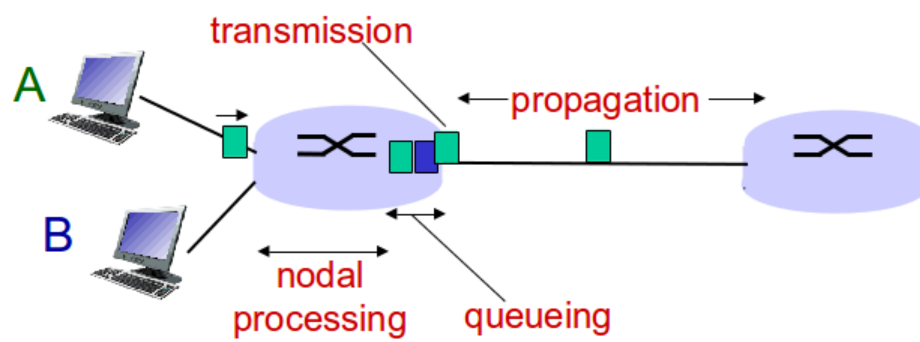
Delay on the way – Summary

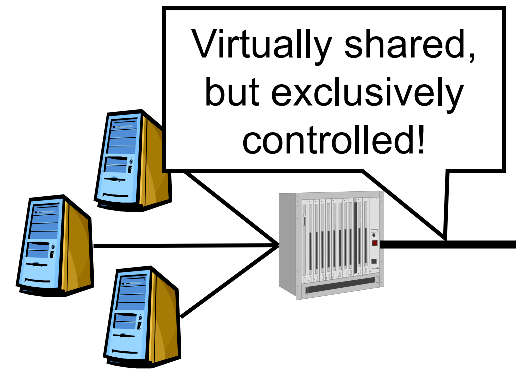
- 1. **Nodal processing**:
  - Check bit errors
  - Determine output
- 2. **Queueing**:
  - Time waiting at output for transmission
  - Depends on congestion at router
- 3. **Transmission delay**:
  - R = link bandwidth (bps)
  - L = packet length (bits)
  - Time to send bits into link: L/R
- 4. **Propagation delay**:
  - d = length of physical link
  - s = propagation speed in medium
  - Propagation delay = d/s
- Just to remind you the issue of queueing ...

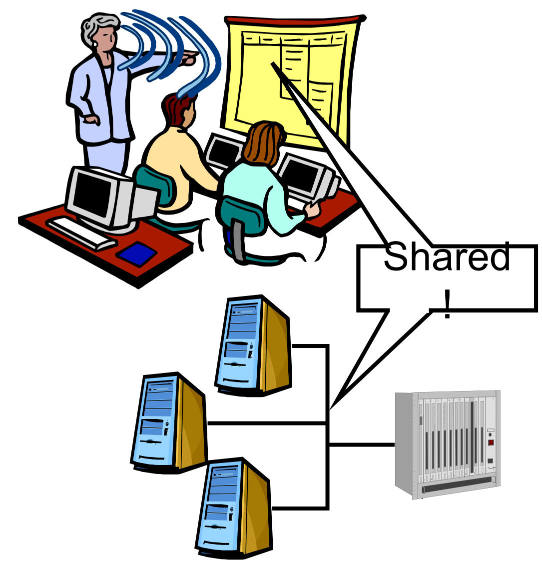


[Cheng, Lehigh Univ., op. cit.]

Multiplexing & shared resources

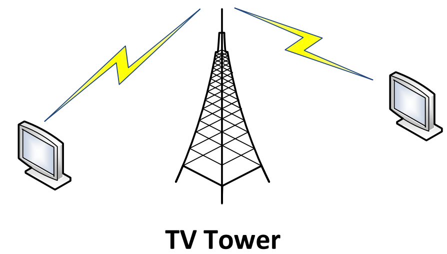
- Multiplexing can be viewed as a means to regulate the access to a resource that is shared by multiple users
  - The switching element/its outgoing line
  - With the switching element as the controller
- Other examples of “shared resources”?
  - Classroom, with “air” as physical medium
- Characteristic: a broadcast medium!
  - Everybody can hear the sender
  - Addressing is necessary (if not sending to all)
    - Unicast (to one)
    - Multicast (to a group)

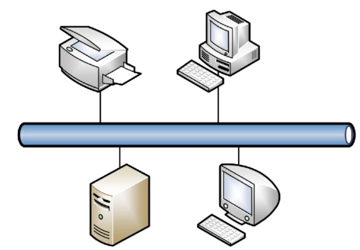


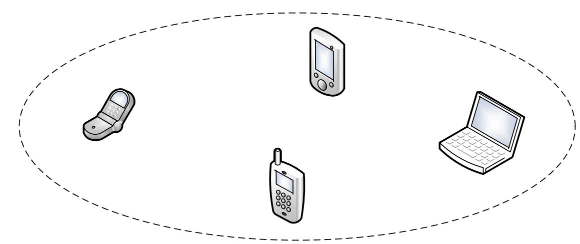


Broadcast Medium & Multiple Access

- Common characteristic of a broadcast medium:
  - Only a single sender at a time,
  - Exclusive access is necessary,
  - Simple to achieve with a multiplexer
- What if no multiplexer is available?
  - E.g., a bus: all nodes connected to a single wireline
  - Or a group wireless devices? Compare: group of kids …
- Exclusive access has to be ensured
  - Rules have to be agreed upon







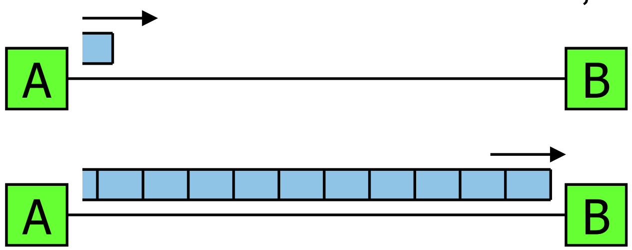
Classification of communication systems

- A simple performance analysis for packet switching networks
- Possible questions
  - How much time does it take to transmit an entire data object?
  - What is the influence of bandwidth and delay?
  - What is the storage capacity of a data connection?

Classification of communication systems

- Bandwidth-delay product
  - Bit rate R, propagation delay D from sender to receiver
  - Simple unidirectional connection, A sends without pause to B

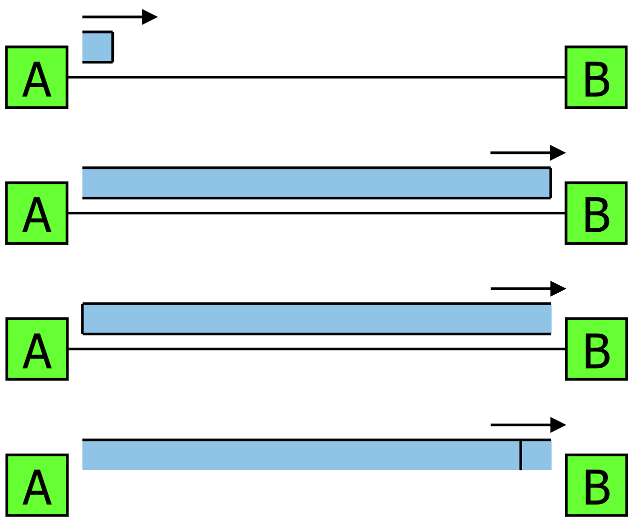
RD > 1:



t = 0: A starts sending

t = D: first bit arrives at B;
meanwhile RD bits was sent

RD < 1:



t = 0: A starts sending

t = D: beginning of the bit arrives at B

t = 1/R: bit completely sent

t = 1/R + D: bit completely received by B

Classification of communication systems

- Cannel buffer capacity in bits
  - $RD = \frac{D}{1/R} = \frac{d/v}{1/R} = \frac{\text{propagation delay}}{\text{time to send a bit}}$

    = number of bits sent while the first bit is on transit to receiver
    = **channel buffer capacity in bits**
  - Example for RD > 1:
    - R = 100 Mbps, d = 4800 km, v = $3 \cdot 10^8$m/s
    - $$RD \square 100 \cdot 10^6 \frac{bits}{s} \cdot \frac{4800 \cdot 10^3 m}{3 \cdot 10^8 m/s} \square 1600 \cdot 10^3 bits \square 195{,}3\, KB$$
  - Example for RD < 1:
    - R = 10 Mbps, d = 10 m, v = $2 \cdot 10^8$m/s
    - $$RD \square 10 \cdot 10^6 \frac{Bits}{s} \cdot \frac{10\, m}{2 \cdot 10^8 m/s} \square 0{,}5\, Bits$$

Classification of communication systems

- Channel buffer capacity in packets

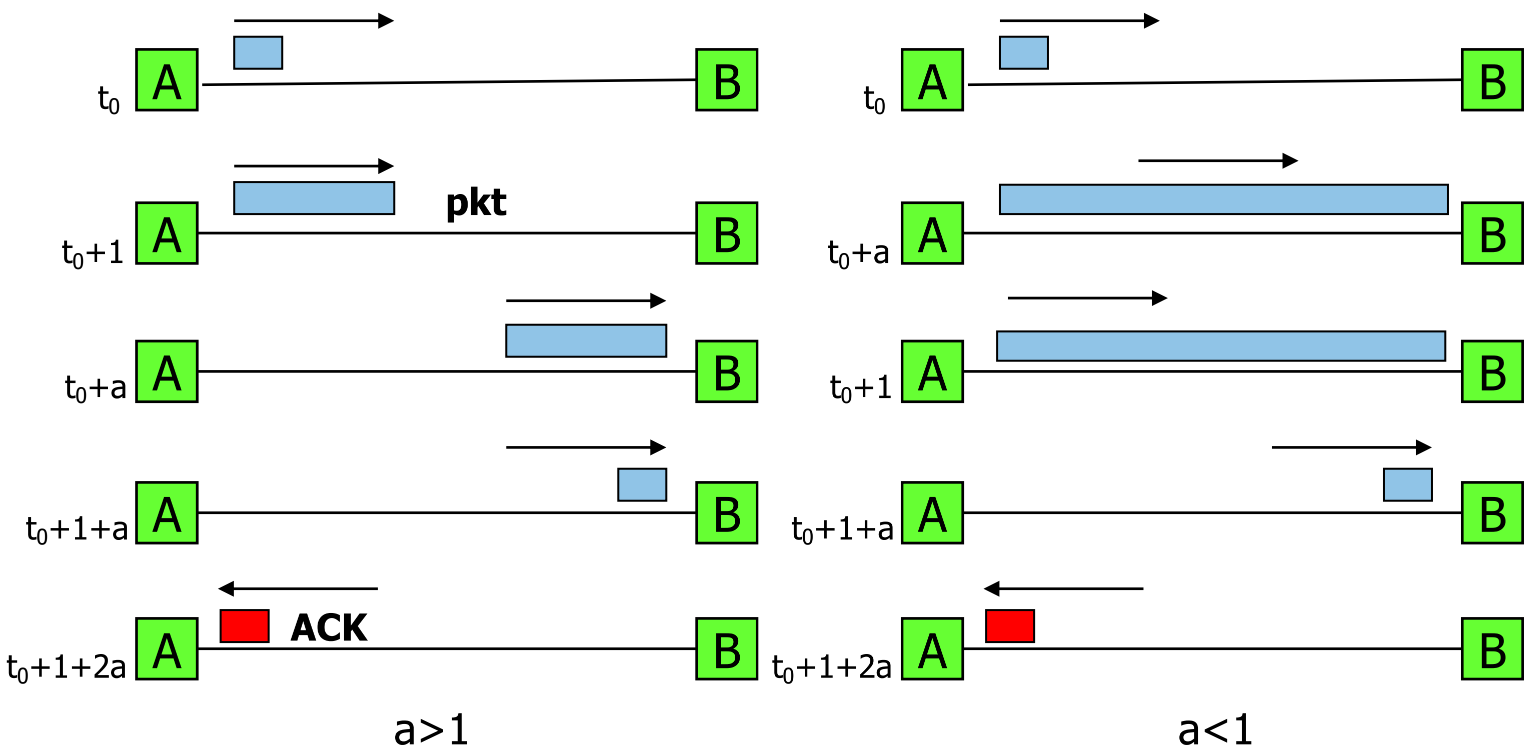
  - For packet size L:

$$a = \frac{RD}{L} = \frac{D}{L/R} = \frac{d/v}{L/R} = \frac{\text{propagation delay}}{\text{time to send a packet}}$$

= number of packets sent while the first bit is on transit to receiver
= **channel buffer capacity in packets**

Classification of communication systems

- Normalization of time by L/R (time to send a single packet), then
  - It takes 1 time slots to send a single packet (1 L/R)
  - It takes a time slots until the first packet arrives at the receiver ($a \cdot L/R = RD/L \cdot L/R = D$)



Examples for the channel storage in packets

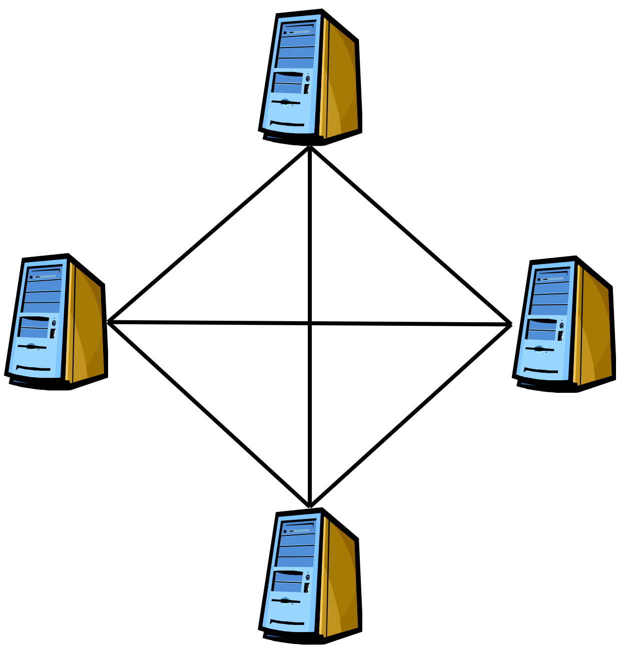
Bit rate (Mbps)	Packet size (Bits)	Distance (km)	a
1	1000	1	0,005
1	1000	3000	15
1	1000	35863	119,5
1	10.000	1	0,0005
1	10.000	3000	1,5
1	10.000	35863	11,95
10	1000	0,05	0,0025
10	1000	0,5	0,025
10	10.000	0,05	0,00025
10	10.000	0,5	0,0025
100	1000	0,1	0,05
100	10.000	0,1	0,005
1000	1000	0,1	0,5
1000	10.000	0,1	0,05

Network topologies

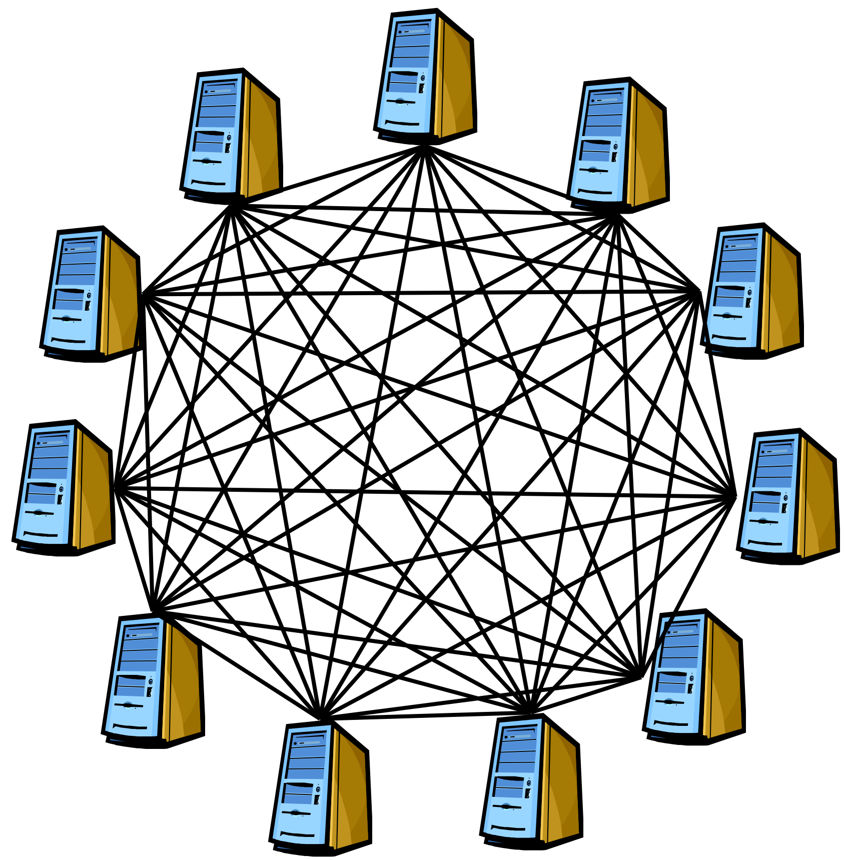
Classification of communication networks

- Topology

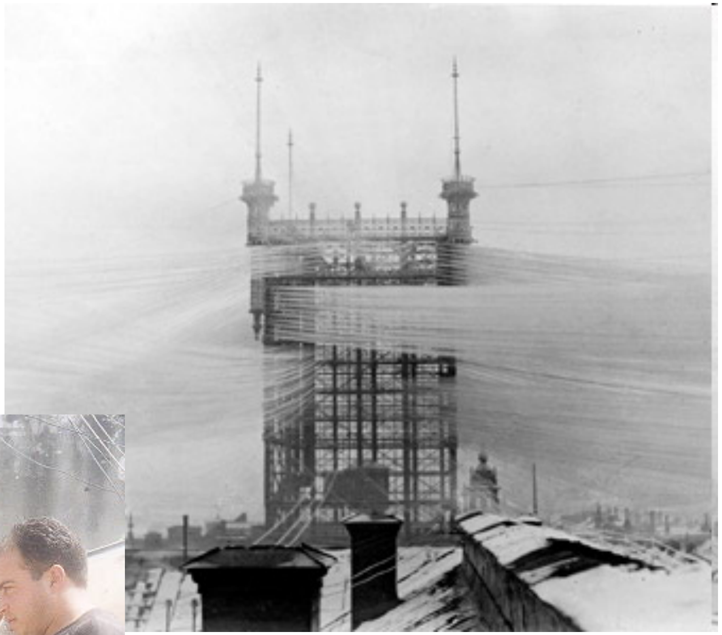
Four nodes



Eleven nodes

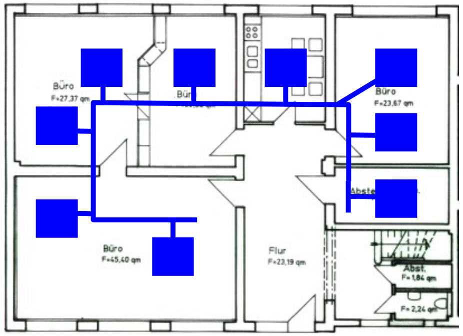


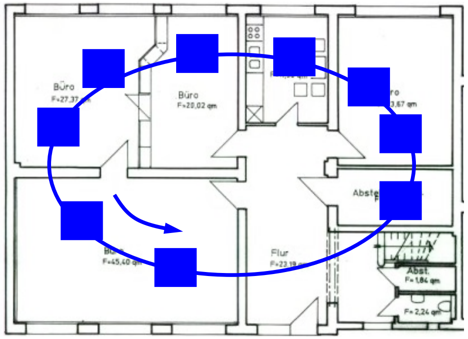
Topology in reality

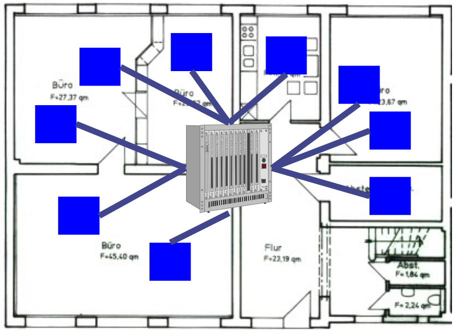


Relevant topologies

- Structured networks
  - Bus, Ring, Star

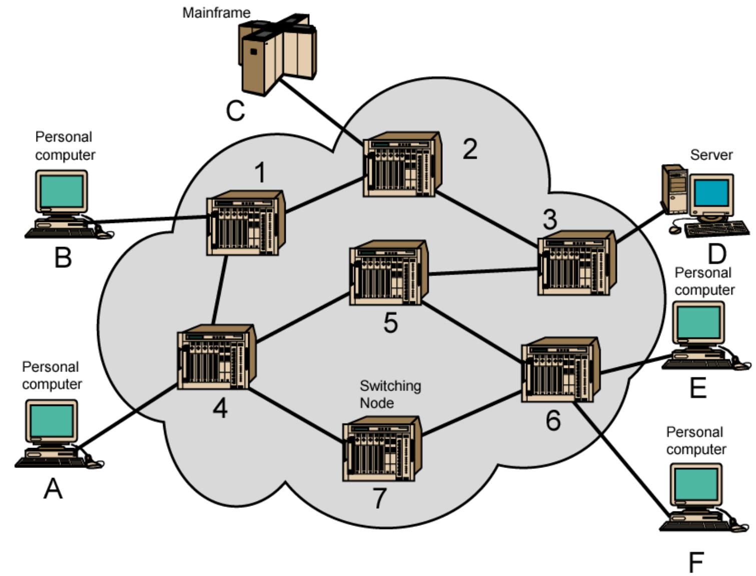






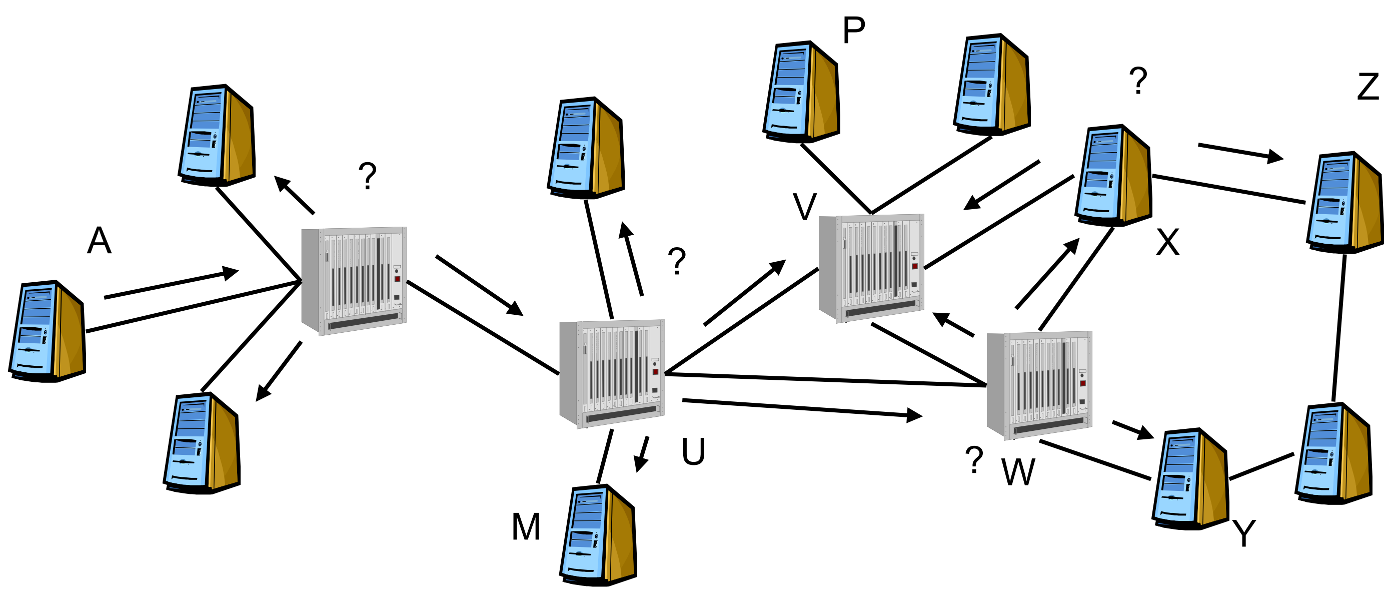
Reminder - Switched Network

- A set of path sections (e.g., electrical cables) and switches,
- “end systems” (terminals/user devices) vs. “switching elements” (routers/bridges)



Forwarding and Next Hop Selection

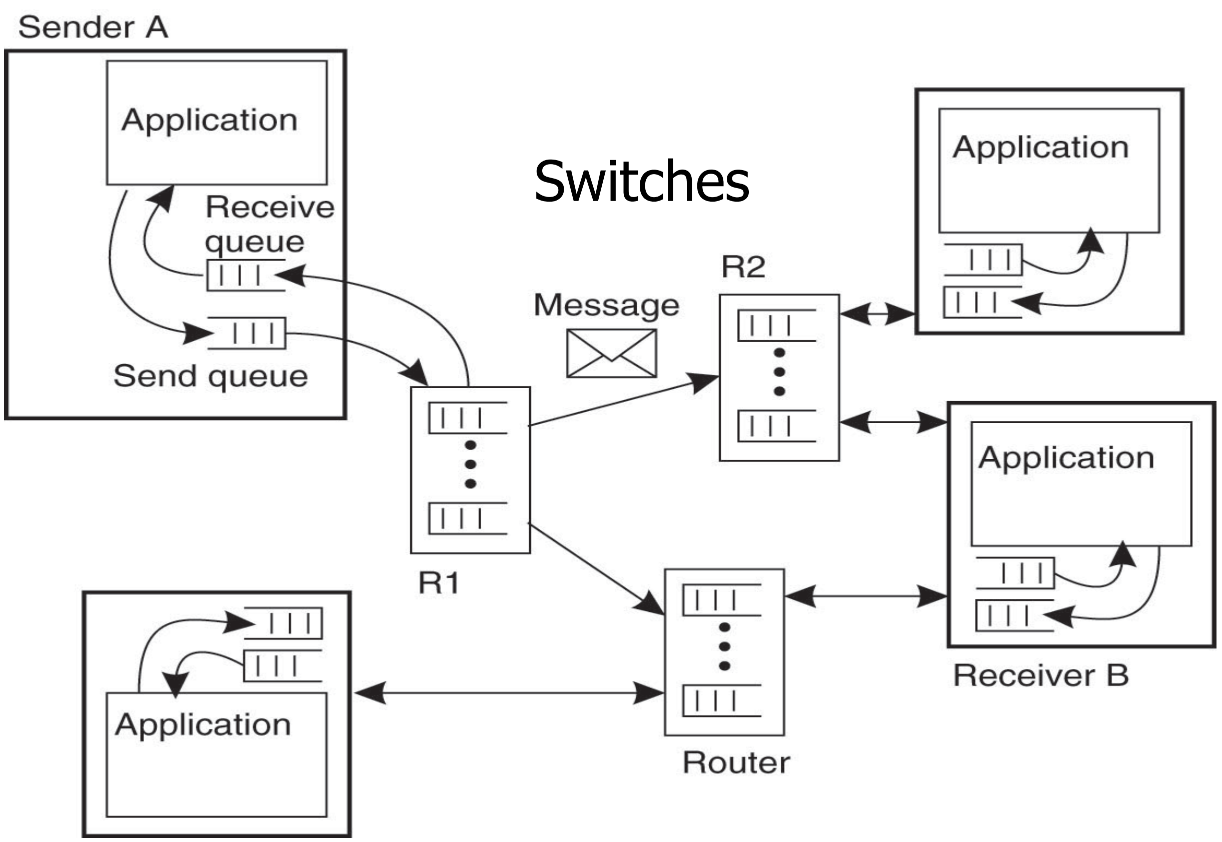
- Switch forwards a packet onto the next "piece"
- Recall: A switching element → a hop towards its destination
- How does a switch know which of its neighbors is the best one towards a destination?
- What is a "good" neighbor, anyway?



Addressing, Routing, Forwarding

- **Name**: whom would you like to reach? (object identity)
- **Address**: where is the object? (locator)
- **Routing**: each switch has to know which of his outputs should be used for a given destination address
  - Hopefully contributes to short “overall trip distance, time”
  - Some understanding of the possible routes is necessary to decide
- **Forwarding**: a packet has arrived. How to “get rid of it” in the way consistent with the routing?
  - With possibly short delay and - hopefully - little delay variation,
  - Structuring of the information describing packet destination and the way routing information is stored matters for execution time

General Architecture of a Message System



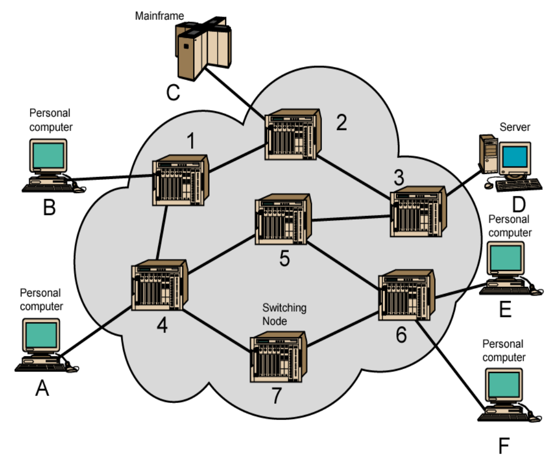
What is the value of a Network?

- Communications networks increase in value as they add members - but by how much?
  - How useful is a single phone using a unique new technology? Two phones? 20 phones? 1 billion of phones …
  - Btw. as by 2017 they are around 5 billion mobile communication users out of worlds population of over 7.8 billions of people
- The Metcalfe´s Law „The value of a communication network is proportional to the square of the user number”
- Other: **n log(n) law** [1]

[1] Briscoe, B., Odlyzko, A., & Tilly, B. (2006). Metcalfe's law is wrong-communications networks increase in value as they add members-but by how much?. IEEE Spectrum, 43(7), 34-39.

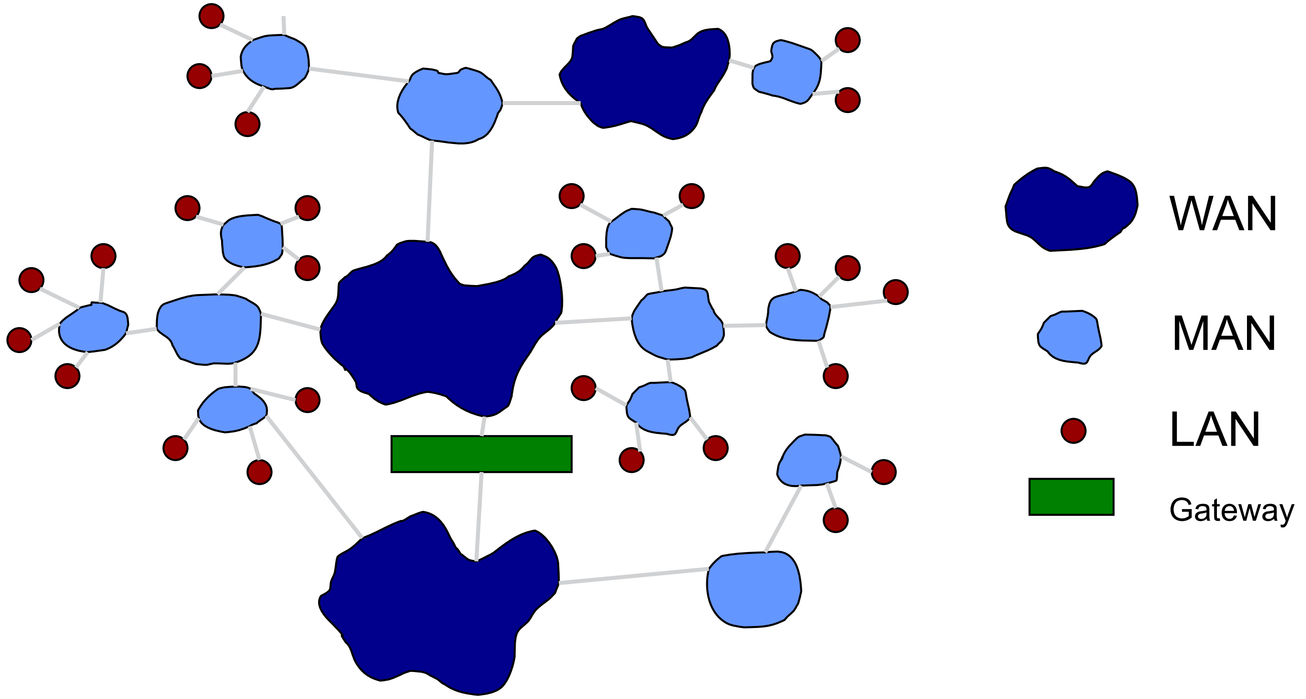
Large Networks need Structure! Why?

- Scaling
  - Remember: each switch knows route to each destination …
  - Hierarchy usually simplifies a lot …
- Locality
  - Close hosts are clustered,
  - Local networks
- Heterogeneity
  - Different applications (e.g., control, sensing) have different requirements,
  - Multiple technologies for access (e.g., wired, wireless)
- Administration
  - Who sets the rules for usage?



Telecommunication Networks Group

Internet: Interoperability vs. Heterogeneity



WAN = Wide Area Network, MAN = Metropolitan Area Network, LAN = Local Area Network

Standardization

Standardization

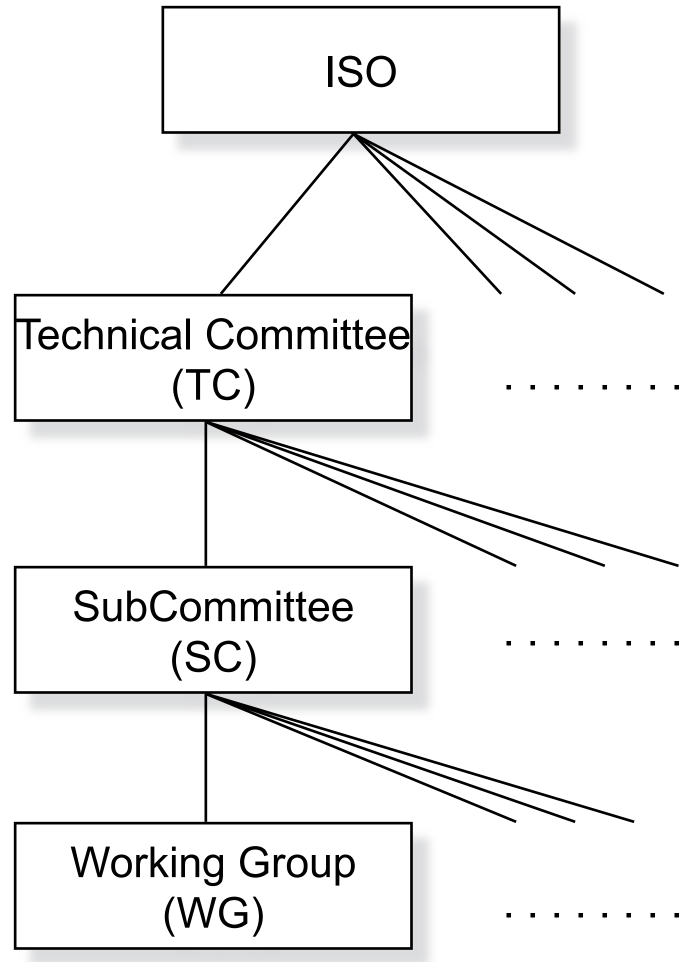
- Essential to realize large, world-wide networks
- Traditionally coordinated by organizations with telecommunications background
  - Established, world-wide coverage, often slow “time to market”
- Internet
  - Internet Engineering Task Force (IETF)
  - Consensus-oriented, focus on “working” implementations
  - Initially fast “time to market”, today much slower
- Many companies try to push their interests
  - “de facto” standards

Standardization: more traditional organizations

- ITU – International Telecommunication Union (formerly CCITT und CCIR)
- CCITT – Consultative Committee on International Telegraphy and Telephony (Comité Consultatif International Télégraphique et Téléphonique)
- CCIR – Consultative Committee on International Radio
- CEPT – Conférence Européenne des Administrations des Postes et des Télécommunications
- ISO – International Organization for Standardization
- DIN – Deutsches Institut für Normung
  - German partner organization of ISO

ISO-Standardization

- WG meetings:
  - Every 6-9 month
  - National organizations get time to accept proposed concepts
  - Afterwards: standardization
    - DP: Draft Proposal
    - DIS: Draft International Standard
    - IS: International Standard
- Standard is more a recommendation for others by means of international consensus
- Very slow process



IETF

- IETF is organized in Areas and Working Groups
  - Members from industry, academia, governments
- Drafts/Proposal can be submitted by anybody
  - „on-demand“
- Standardization requires at least two independent implementations
- Informal voting in working groups
  - „Humming“
  - Three meetings per year
- Result:
  - RFC – request for comment (the standard)
  - FYI – informal or informational