Switching Technology
S38.3165

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General

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Goals of the course

- **Understand what switching is about**
- **Understand the basic structure and functions of a switching system**
- **Understand the role of a switching system in a transport network**
- **Understand how a switching system works**
- **Understand technology related to switching**
- **Understand how conventional circuit switching is related to packet switching**

Course outline

- Introduction to switching
  - switching in general
  - switching modes
  - transport and switching
- Switch fabrics
  - basics of fabric architectures
  - fabric structures
  - path search, self-routing and sorting

Course outline

- Switch implementations
  - PDH switches
  - ATM switches
  - routers
- Optical switching
  - basics of WDM technology
  - components for optical switching
  - optical switching concepts

Course requirements

- **Preliminary information**
  - S-38.188 Tietoliikenneverkot or
    S-72.423 Telecommunication Systems
    (or a corresponding course)
- **12 lectures (á 3 hours)**
- **6 exercises (á 2 hours)**
- **Grading**
  - Calculus exercises give 0 to 6 bonus points, which are valid in exams in 2007
  - Examination, max 30 points
  - Total grade = exam points + bonus points

Course material

- Lecture notes
- *Understanding Telecommunications* 1, Ericsson & Telia, Studentlitteratur, 2001, ISBN 91-44-00212-2, Chapters 2-4.
- J. Hui: *Switching and traffic theory for integrated broadband networks*, Kluwer Academic Publ., 1990, ISBN 0-7923-9061-X, Chapters 1 - 6.
- H. J. Chao, C. H. Lam and E. Oki: *Broadband Packet Switching technologies – A Practical Guide to ATM Switches and IP routers*, John Wiley & Sons, 2001, ISBN 0-471-00454-5.
- T.E. Stern and K. Bala: *Multiwavelength Optical Networks: A Layered Approach*, Addison-Wesley, 1999, ISBN 0-201-30967-X.

Additional reading

- A. Pattavina: *Switching Theory - Architecture and Performance in Broadband ATM Networks*, John Wiley & Sons (Chichester), 1998, IBSN 0-471-96338-0, Chapters 2 - 4.
- R. Ramaswami and K. Sivarajan, *Optical Networks, A Practical Perspective*, Morgan Kaufman Publ., 2nd Ed., 2002, ISBN 1-55860-655-6.

Introduction to switching

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Introduction to switching

- Switching in general
- Switching modes
- Transport and switching

Switching in general

ITU-T specification for switching:

"The establishing, on-demand, of an individual connection from a desired inlet to a desired outlet within a set of inlets and outlets for as long as is required for the transfer of information."

inlet/outlet = a line or a channel

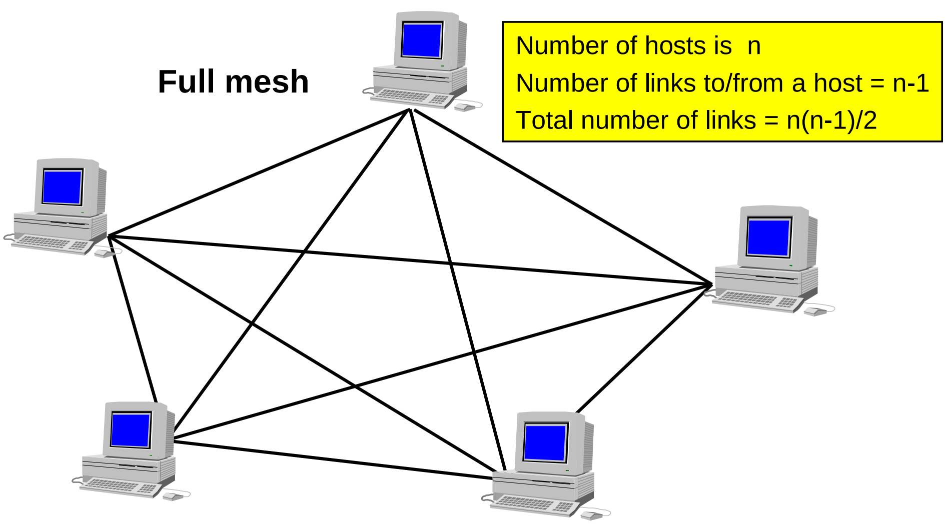
Switching in general (cont.)

- Switching implies directing of information flows in communications networks based on known rules
- Switching takes place in specialized network nodes
- Data switched on bit, octet, frame or packet level
- Size of a switched data unit is variable or fixed

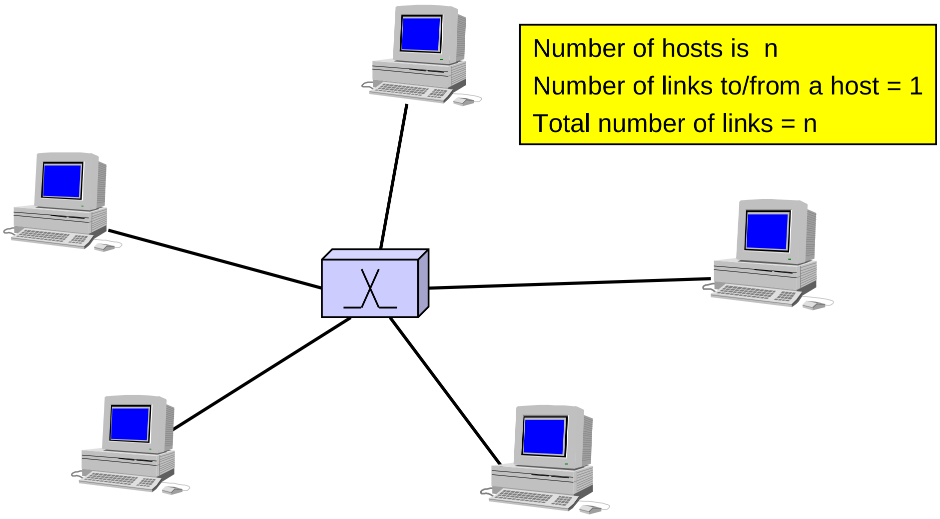
Why switching ?

- Switches allow reduction in overall network cost by reducing number and/or cost of transmission links required to enable a given user population to communicate
- Limited number of physical connections implies need for sharing of transport resources, which means
  - better utilization of transport capacity
  - use of switching
- Switching systems are central components in communications networks

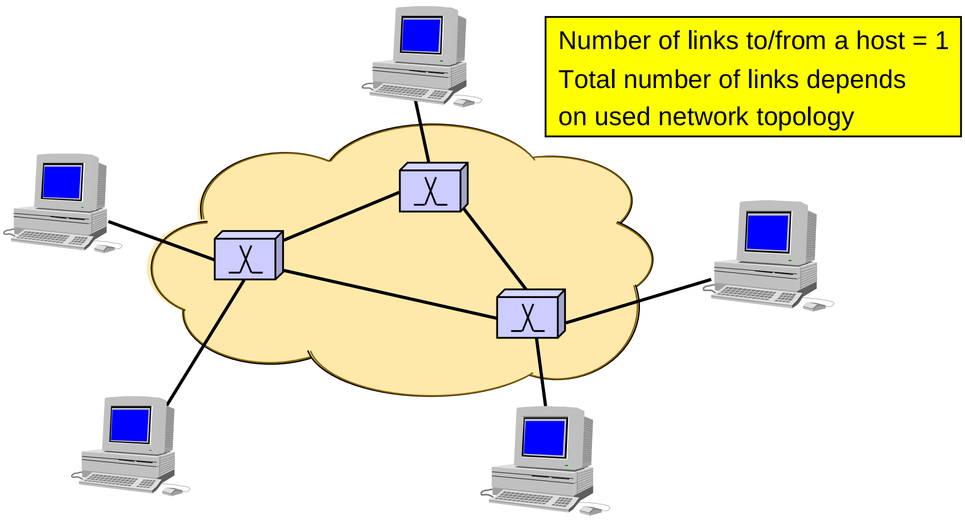
Full connectivity between hosts



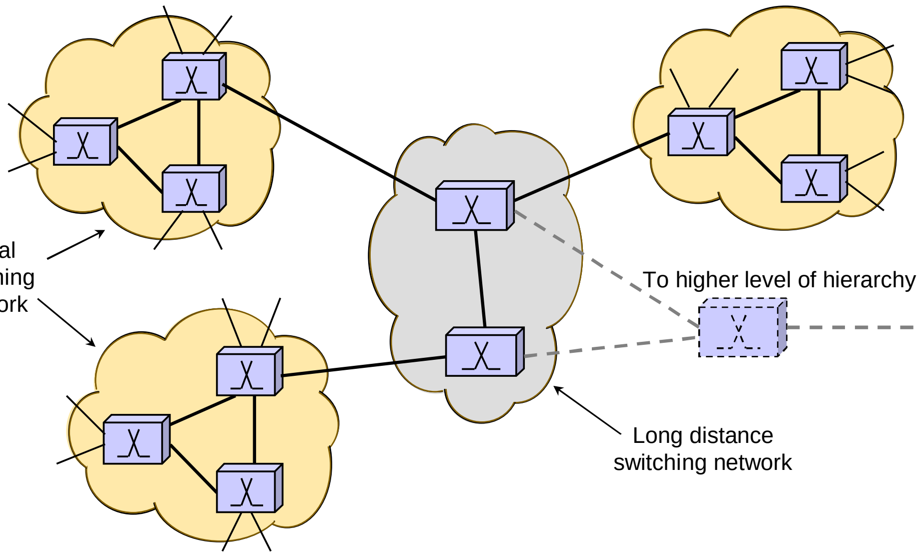
Centralized switching



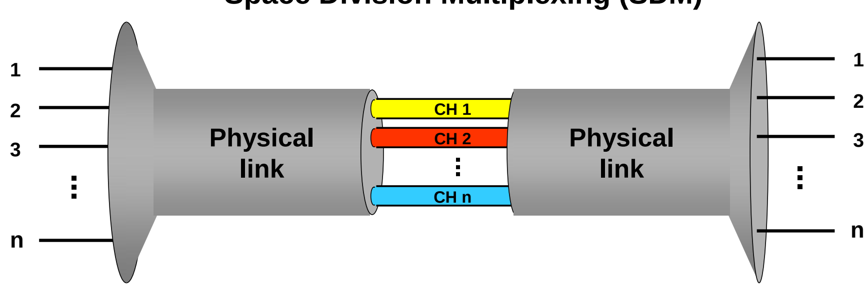
Switching network to connect hosts



Hierarchy of switching networks



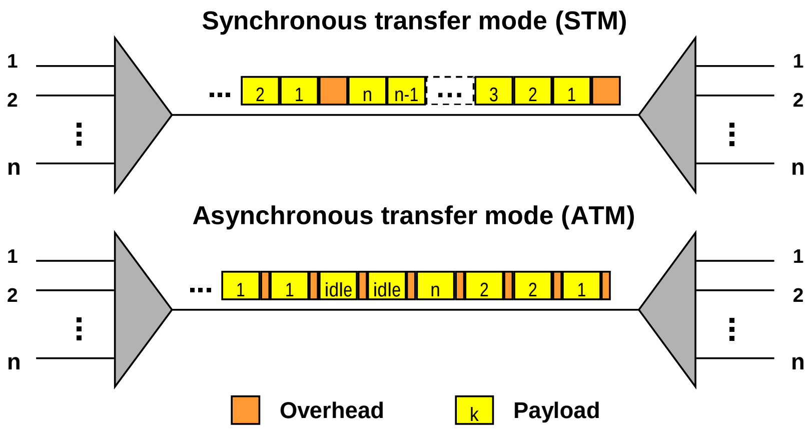
Sharing of link capacity



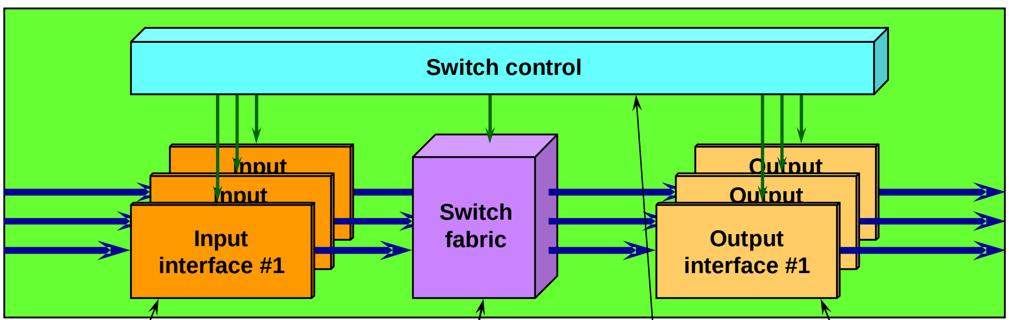
Space to be divided:
- **physical cable or twisted pair**
- **frequency**
- **light wave**

Sharing of link capacity (cont.)

Time Division Multiplexing (TDM)



Main building blocks of a switch



- input signal reception
- error checking and recovery
- incoming frame disassembly
- buffering
- routing/switching decision

- switching of data units from input interfaces to destined output interfaces
- limited buffering

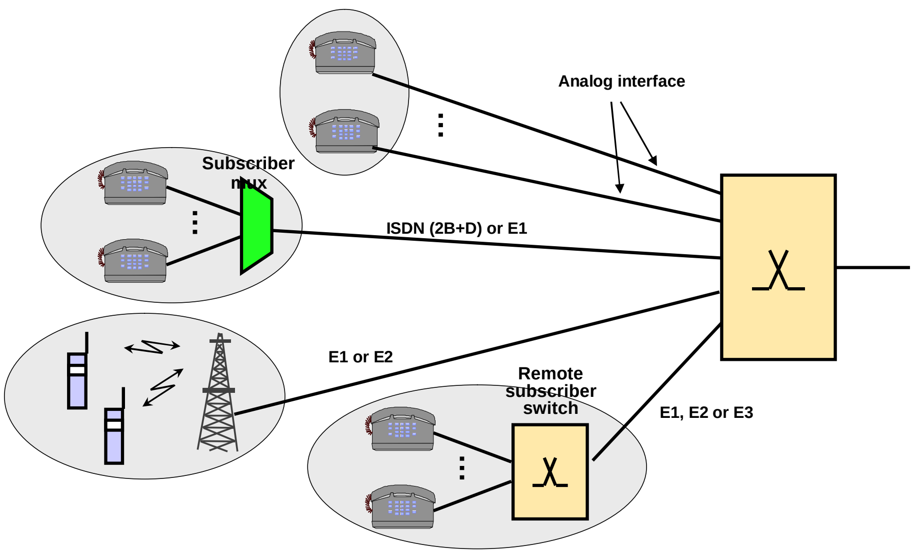
- buffering, prioritizing and scheduling
- outgoing frame assembly
- output signal generation and transmission

- processing of signaling/connection control information
- configuration and control of input/output interfaces and switch fabric

Heterogeneity by switching

- Switching systems allow heterogeneity among terminals
  - terminals of different processing and transmission speeds supported
  - terminals may implement different sets of functionality
- and heterogeneity among transmission links by providing a variety of interface types
  - data rates can vary
  - different link layer framing applied
  - optical and electrical interfaces
  - variable line coding

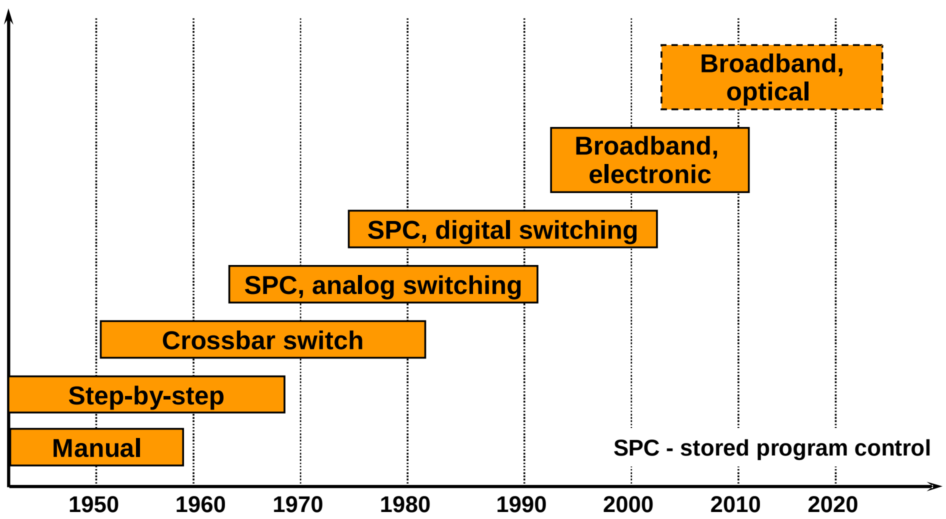
Heterogeneity by switching (cont.)



Basic types of witching networks

- Statically switched networks
  - connections established for longer periods of time (typically for months or years)
  - management system used for connection manipulation
- Dynamically switched networks
  - connections established for short periods of time (typically from seconds to tens of minutes)
  - active signaling needed to manipulate connections
- Routing networks
  - no connections established - no signaling
  - each data unit routed individually through a network
  - routing decision made dynamically or statically

Development of switching technologies



Source: *Understanding Telecommunications* 1, Ericsson & Telia, Studentlitteratur, 2001.

Development of switching tech. (cont.)

- Manual systems
  - in the infancy of telephony, exchanges were built up with manually operated switching equipment (the first one in 1878 in New Haven, USA)
- Electromechanical systems
  - manual exchanges were replaced by automated electromechanical switching systems
  - a patent for automated telephone exchange in 1889 (Almon B. Strowger)
  - step-by-step selector controlled directly by dial of a telephone set
  - developed later in the direction of register-controlled system in which number information is first received and analyzed in a register – the register is used to select alternative switching paths (e.g. 500 line selector in 1923 and crossbar system in 1937)
  - more efficient routing of traffic through transmission network
  - increased traffic capacity at lower cost

Development of switching tech. (cont.)

- Computer-controlled systems
  - FDM was developed round 1910, but implemented in 1950's (ca. 1000 channels transferred in a coaxial cable)
  - PCM based digital multiplexing introduced in 1970's – transmission quality improved – costs reduced further when digital group switches were combined with digital transmission systems
  - computer control became necessary - the first computer controlled exchange put into service in 1960 (in USA)
  - strong growth of data traffic resulted in development of separate data networks and switches – advent of packet switching (sorting, routing and buffering)
  - N-ISDN network combined telephone exchange and packet data switches
  - ATM based cell switching formed basis for B-ISDN
  - next step is to use optical switching with electronic switch control – all optical switching can be seen in the horizon

Challenges of modern switching

- Support of different traffic profiles
  - constant and variable bit rates, bursty traffic, etc.
- Simultaneous switching of highly different data rates
  - from kbits/s rates to Gbits/s rates
- Support of varying delay requirements
  - constant and variable delays
- Scalability
  - number of input/output links, link bit rates, etc.
- Reliability
- Cost
- Throughput

Switching modes

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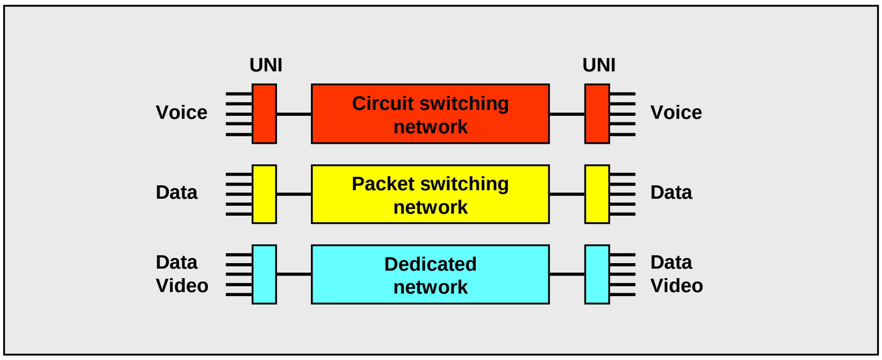
Narrowband network evolution

- Early telephone systems used analog technology - frequency division multiplexing (FDM) and space division switching (SDS)
- When digital technology evolved time division multiplexing (TDM) and time division switching (TDS) became possible
- Development of electronic components enabled integration of TDM and TDS => Integrated Digital Network (IDN)
- Different and segregated communications networks were developed
  - circuit switching for voice-only services
  - packet switching for (low-speed) data services
  - dedicated networks, e.g. for video and specialized data services

Segregated transport

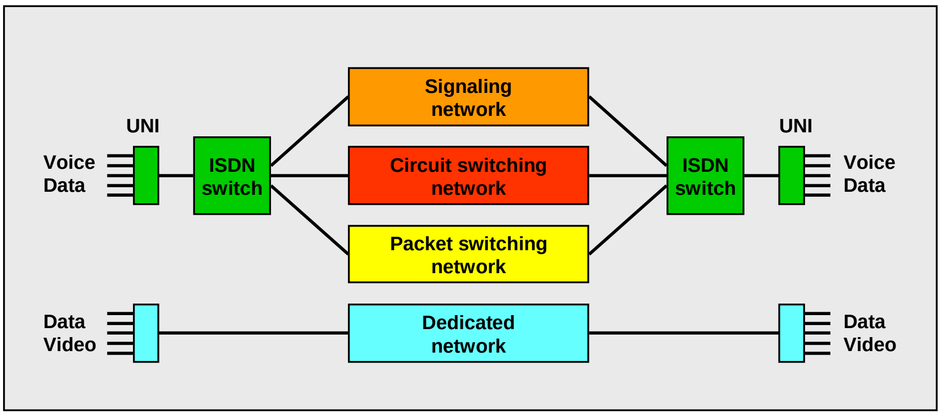


UNI – User Network Interface

Narrowband network evolution (cont.)

- Service integration became apparent to better utilize communications resources
  => IDN developed to ISDN (Integrated Services Digital Network)
- ISDN offered
  - a unique user-network interface to support basic set of narrowband services
  - integrated transport and full digital access
  - inter-node signaling (based on packet switching)
  - packet and circuit switched end-to-end digital connections
  - three types of channels (B=64 kbit/s, D=16 kbit/s and H=nx64 kbit/s)
- Three types of long-distance interconnections
  - circuit switched, packet switched and signaling connections
- Specialized services (such as video) continued to be supported by separate dedicated networks

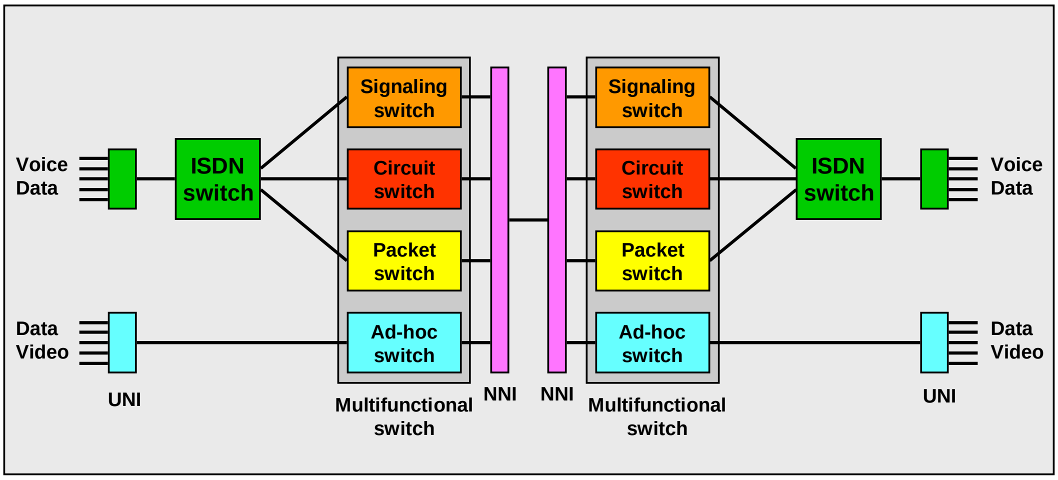
Integrated transport



Broadband network evolution

- Progress in optical technologies enabled huge transport capacities
  => integration of transmission of all the different networks
  (NB and BB) became possible
- Switching nodes of different networks co-located to configure multifunctional switches
  – each type of traffic handled by its own switching module
- Multifunctional switches interconnected by broadband integrated transmission (BIT) systems terminated onto network-node interfaces (NNI)
- BIT accomplished with partially integrated access and segregated switching

Narrowband-integrated access and broadband-integrated transmission

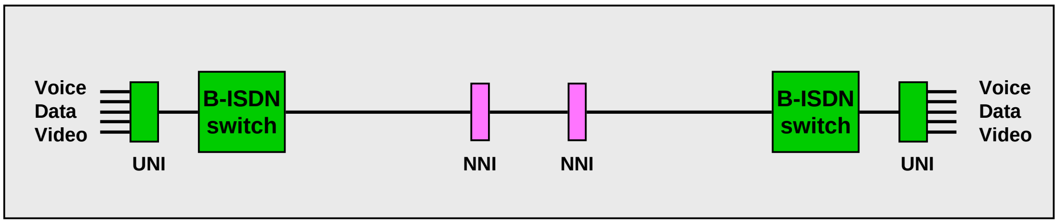


NNI - Network-to-Network Interface

Broadband network evolution (cont.)

- N-ISDN had some limitations:
  - low bit rate channels
  - no support for variable bit rates
  - no support for large bandwidth services
- Connection oriented packet switching scheme, i.e., ATM (Asynchronous Transfer Mode), was developed to overcome limitations of N-ISDN
  => B-ISDN concept
  => integrated broadband transport and switching (no more need for specialized switching modules or dedicated networks)

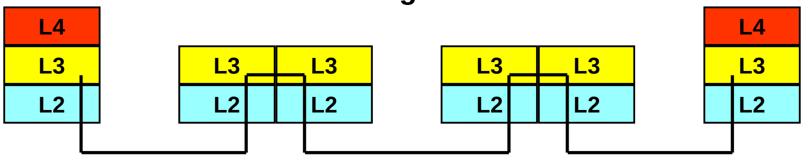
Broadband integrated transport



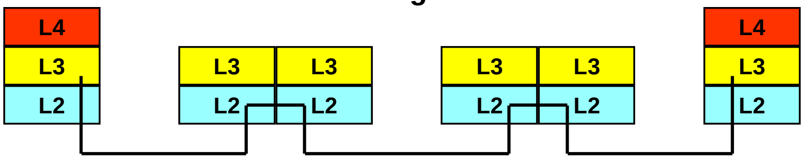
UNI – User Network Interface
NNI – Network-to-Network Interface

OSI definitions for routing and switching

Routing on L3



Switching on L2

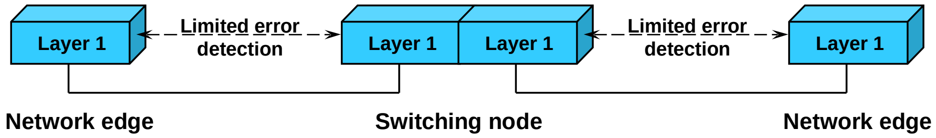


Switching modes

- Circuit switching
- Cell and frame switching
- Packet switching
  - Routing
  - Layer 3 - 7 switching
  - Label switching

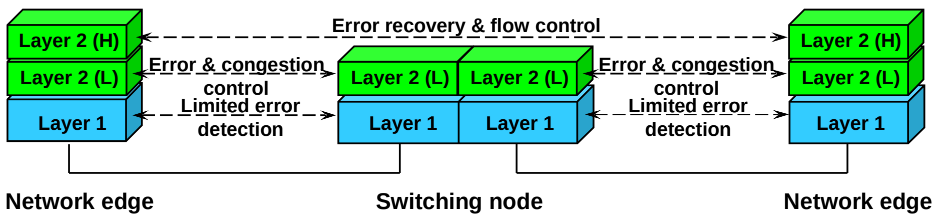
Circuit switching

- End-to-end circuit established for a connection
- Signaling used to set-up, maintain and release circuits
- Circuit offers constant bit rate and constant transport delay
- Equal quality offered to all connections
- Transport capacity of a circuit cannot be shared
- Applied in conventional telecommunications networks (e.g. PDH/PCM and N-ISDN)



Cell switching

- Virtual circuit (VC) established for a connection
- Data transported in fixed length frames (cells), which carry information needed for routing cells along established VCs
- Forwarding tables in network nodes

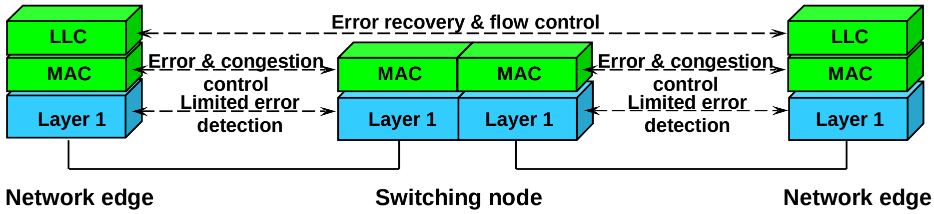


Cell switching (cont.)

- Signaling used to set-up, maintain and release VCs as well as update forwarding tables
- VCs offer constant or variable bit rates and transport delay
- Transport capacity of links shared by a number of connections (statistical multiplexing)
- Different quality classes supported
- Applied, e.g. in ATM networks

Frame switching

- Virtual circuits (VC) established usually for virtual LAN connections
- Data transported in variable length frames (e.g. Ethernet frames), which carry information needed for routing frames along established VCs
- Forwarding tables in network nodes

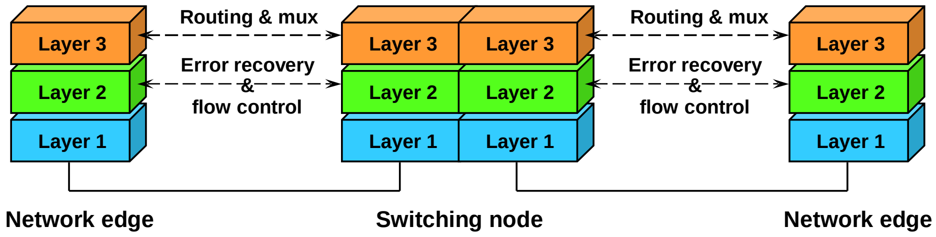


Frame switching (cont.)

- VCs based, e.g., on 12-bit Ethernet VLAN IDs (Q-tag) or 48-bit MAC addresses
- Signaling used to set-up, maintain and release VCs as well as update forwarding tables
- VCs offer constant or variable bit rates and transport delay
- Transport capacity of links shared by a number of connections (statistical multiplexing)
- Different quality classes supported
- Applied, e.g. in offering virtual LAN services for business customers

Packet switching

- No special transport path established for a connection
- Variable length data packets carry information used by network nodes in making forwarding decisions
- No signaling needed for connection setup



Packet switching (cont.)

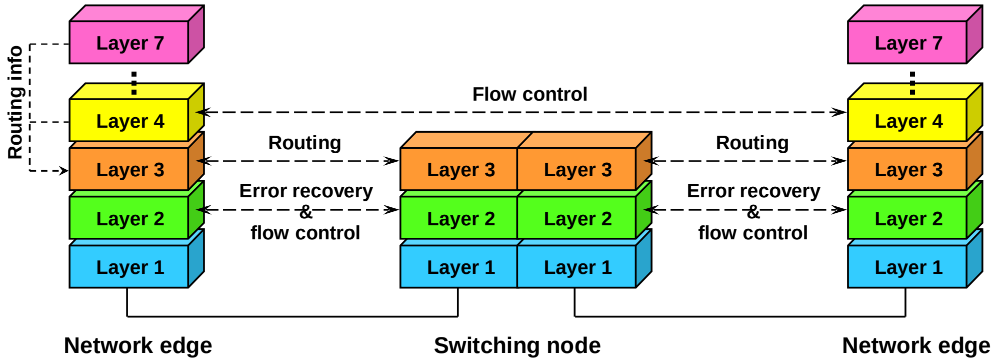
- Forwarding tables in network nodes are updated by routing protocols
- No guarantees for bit rate or transport delay
- Best effort service for all connections in conventional packet switched networks
- Transport capacity of links shared effectively
- Applied in IP (Internet Protocol) based networks

Layer 3 - 7 switching

- L3-switching evolved from the need to speed up (IP based) packet routing
- L3-switching separates routing and forwarding
- A communication path is established based on the first packet associated with a flow of data and succeeding packets are switched along the path (i.e. software based routing combined with hardware based one)
- Notice: In wire-speed routing, traditional routing is implemented in hardware to eliminate performance bottlenecks associated with software based routing (i.e., conventional routing reaches/surpasses L3-switching speeds)

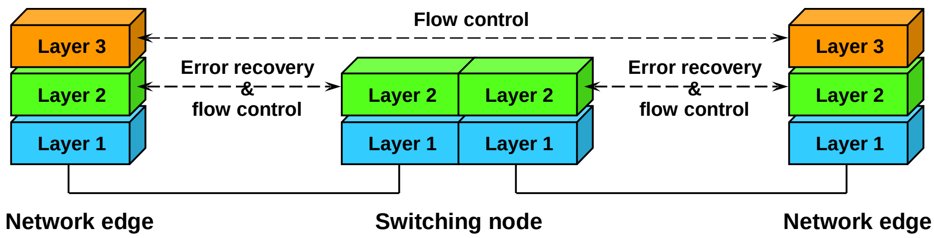
Layer 3 - 7 switching (cont.)

- In L4 - L7 switching, forwarding decisions are based not only on MAC address of L2 and destination/source address of L3, but also on application port number of L4 (TCP/UDP) and on information of layers above L4



Label switching

- Evolved from the need to speed up connectionless packet switching and utilize L2-switching in packet forwarding
- A label switched path (LSP) established for a connection
- Forwarding tables in network nodes



Label switching (cont.)

- Signaling used to set-up, maintain and release LSPs
- A label is inserted in front of a L3 packet (behind L2 frame header)
- Packets forwarded along established LSPs by using labels in L2 frames
- Quality of service supported
- Multi-Protocol Label Switching (MPLS) is a standardized label switching concept and is used to carry IP packet, e.g. over ATM, Ethernet and PPP
- Generalized label switching scheme (GMPLS) extends MPLS to be applied also in optical networks, i.e., enables light waves to be used as LSPs

Latest directions in switching

- The latest switching schemes developed to utilize Ethernet based transport
- Scalability of the basic Ethernet concept has been the major problem, i.e., 12-bit limitation of VLAN ID
- Modifications to the basic Ethernet frame structure have been proposed to extend Ethernet's addressing capability, e.g., Q-in-Q, Mac-in-Mac, Virtual MAN and Ethernet-over-MPLS
- Standardization bodies favor concepts (such as Q-in-Q and VMAN) that are backward compatible with the legacy Ethernet frame
- Signaling solutions still need further development

Transmission techniques and multiplexing hierarchies

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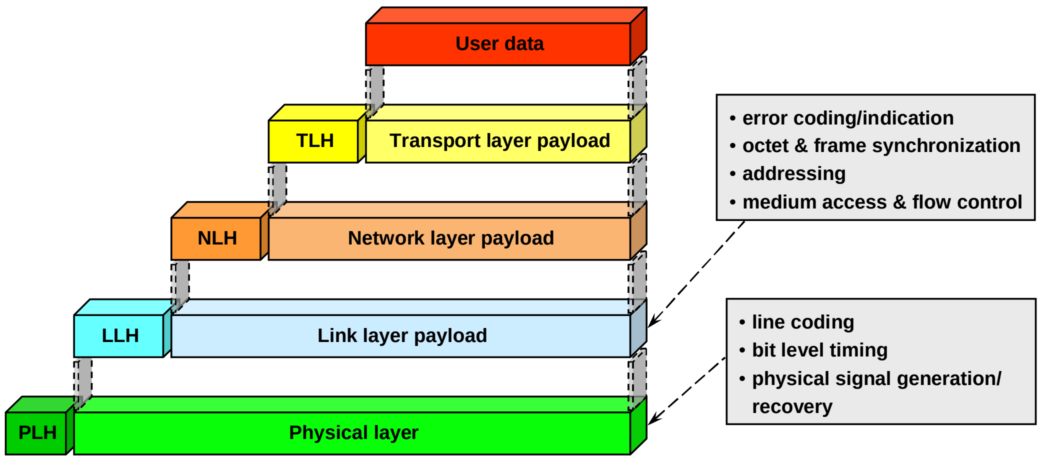
Transmission techniques and multiplexing hierarchies

- Transmission of data signals
- Timing and synchronization
- Transmission techniques and multiplexing
  - PDH
  - ATM
  - IP/Ethernet
  - SDH/SONET
  - OTN
  - GFP

Transmission of data signals

- Encapsulation of user data into layered protocol structure
- Physical and link layers implement functionality that have relevance to switching
  – multiplexing of transport signals (channels/connections)
  – medium access and flow control
  – error indication and recovery
  – bit, octet and frame level timing/synchronization
  – line coding (for spectrum manipulation and timing extraction)

Encapsulation of user data



Synchronization of transmitted data

- Successful transmission of data requires bit, octet, frame and packet level synchronism
- Synchronous systems (e.g. PDH and SDH) carry additional information (embedded into transmitted line signal) for accurate recovery of clock signals
- Asynchronous systems (e.g. Ethernet) carry additional bit patterns to synchronize receiver logic

Timing accuracy

- Inaccuracy of frequency classified in telecom networks to
  - jitter (short term changes in frequency > 10 Hz)
  - wander (< 10 Hz fluctuation)
  - long term frequency shift (drift or skew)
- To maintain required timing accuracy, network nodes are connected to a hierarchical synchronization network
  - Universal Time Coordinated (UTC): error in the order of 10^{-13}
  - Error of Primary Reference Clock (PRC) of the telecom network in the order of 10^{-11}

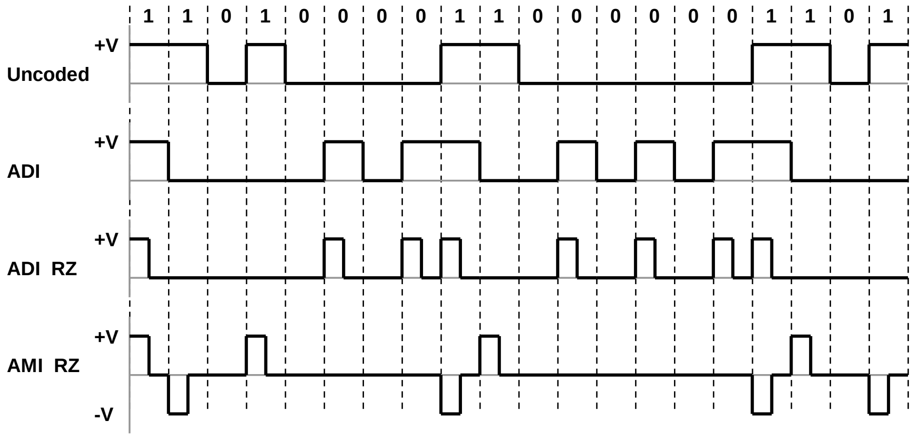
Timing accuracy (cont.)

- Inaccuracy of clock frequency causes
  - degraded quality of received signal
  - bit errors in regeneration
  - slips: in PDH networks a frame is duplicated or lost due to timing difference between the sender and receiver
- Based on applied synchronization method, networks are divided into
  - fully synchronous networks (e.g. SDH)
  - plesiochronous networks (e.g. PDH), sub-networks have nominally the same clock frequency but are not synchronized to each other
  - mixed networks

Methods for bit level timing

- To obtain bit level synchronism receiver clocks must be synchronized to incoming signal
- Incoming signal must include transitions to keep receiver's clock recovery circuitry in synchronism
- Methods to introduce line signal transitions
  - Line coding
  - Block coding
  - Scrambling

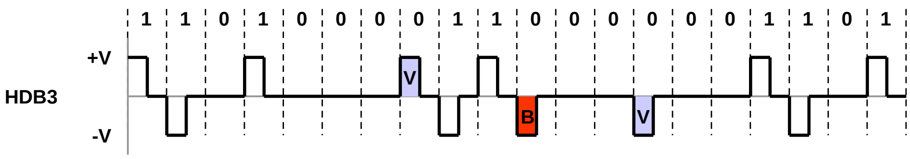
Line coding



ADI - Alternate Digit Inversion
ADI RZ - Alternate Digit Inversion Return to Zero
AMI RZ - Alternate Mark Inversion Return to Zero

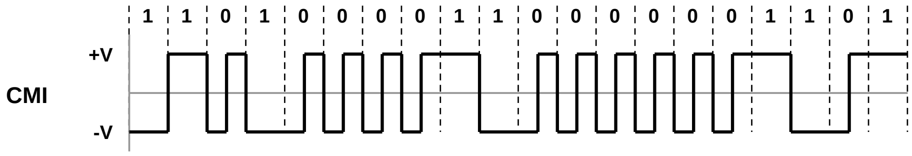
Line coding (cont.)

- ADI, ADI RZ and codes alike introduce DC balance shift => clock recovery becomes difficult
- AMI and AMI RZ introduces DC balance, but lacks effective ability to introduce signal transitions
- HDB3 (**High Density Bipolar 3**) code, used in PDH systems, guarantees a signal transition at least every fourth bit
  - 0000 coded by 000V when there is an odd number of pulses since the last violation (V) pulse
  - 0000 coded by B00V when there is an even number of pulses since the last violation pulse



Line coding (cont.)

- When bit rates increase (> 100 Mbit/s) jitter requirements become tighter and signal transitions should occur more frequently than in HDB3 coding
- CMI (Coded Mark Inversion) coding was introduced for electronic differential links and for optical links
- CMI doubles bit rate on transmission link => higher bit rate implies larger bandwidth and shortened transmission distance



Block coding

- Entire blocks of *n* bits are replaced by other blocks of *m* bits (*m* > *n*)
- *nBmB* block codes are usually applied on optical links by using on-off keying
- Block coding adds variety of “1”s and “0”s to obtain better clock synchronism and reduced jitter
- Redundancy in block codes (in the form of extra combinations) enables error recovery to a certain extent
- When *m*>*n* the coded line signal requires larger bandwidth than the original signal
- Examples: 4B5B (FDDI), 5B6B (E3 optical links) and 8B10B (GbE)

Coding examples

4B5B coding

Input word	Output word	Other output words	
0000	11110	00000	Quiet line symbol
0001	01001	11111	Idle symbol
0010	10100	00100	Halt line symbol
0011	10101	11000	Start symbol
0100	01010	10001	Start symbol
0101	01011	01101	End symbol
0110	01110	00111	Reset symbol
0111	01111	11001	Set Symbol
1000	10010	00001	Invalid
1001	10011	00010	Invalid
1010	10110	00011	Invalid
1011	10111	00101	Invalid
1100	11010	00110	Invalid
1101	11011	01000	Invalid
1110	11100	01100	Invalid
1111	11101	10000	Invalid

5B6B coding

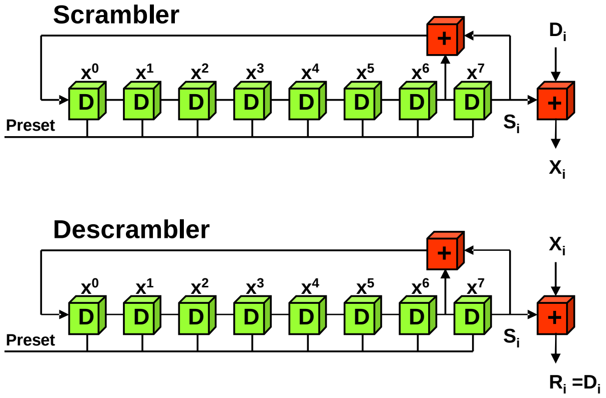
Input word	Output word
00000	101011
00001	101010
00010	101001
00011	111000
...	...
11100	010011
11101	010111
11110	011011
11111	011100

Scrambling

- Data signal is changed bit by bit according to a separate repetitive sequence (to avoid long sequences of “1”s or “0”s)
- Steps of the sequence give information on how to handle bits in the signal being coded
- A scrambler consists of a feedback shift register described by a polynomial (**$x^N + \dots + x^m + \dots + x^k + \dots + x + 1$)**
- Polynomial specifies from where in the shift register feedback is taken
- Output bit rate is the same as the input bit rate
- Scrambling is not as effective as line coding

Scrambler example

SDH/STM-1 uses x^7+x^6+1 polynomial



$X_i = S_i \oplus D_i$

$R_i = S_i \oplus X_i$
$= S_i \oplus (S_i \oplus D_i) = D_i$

Methods for octet and frame level timing

- Frame alignment bit pattern
- Start of frame signal
- Use of frame check sequence

Frame alignment sequence

- Data frames carry special frame alignment bit patterns to obtain octet and frame level synchronism
- Data bits scrambled to avoid misalignment
- Used in networks that utilize synchronous transmission, e.g. in PDH, SDH and OTN
- Examples
  - PDH E1 frames carry bit sequence 0011011 in every other frame (even frames)
  - SDH and OTN frames carry a six octet alignment sequence (hexadecimal form: F6 F6 F6 28 28 28) in every frame

Start of frame signal

- Data frames carry special bit patterns to synchronize receiver logic
- False synchronism avoided for example by inserting additional bits into data streams
- Used in synchronous and asynchronous networks, e.g., Ethernet and HDLC
- Examples
  - Ethernet frames are preceded by a 7-octet preamble field (10101010) followed by a start-of-frame delimiter octet (10101011)
  - HDLC frames are preceded by a flag byte (0111 1110)

Frame check sequence

- Data frames carry no special bit patterns for synchronization
- Synchronization is based on the use of error indication and correction fields
  – CRC (Cyclic Redundancy Check) calculation
- Used in bit synchronous networks such as ATM and GFP (Generic Framing Procedures)
- Example
  – ATM cell streams can be synchronized to HEC (Header Error Control) field, which is calculated across ATM cell header