6. Access Networks

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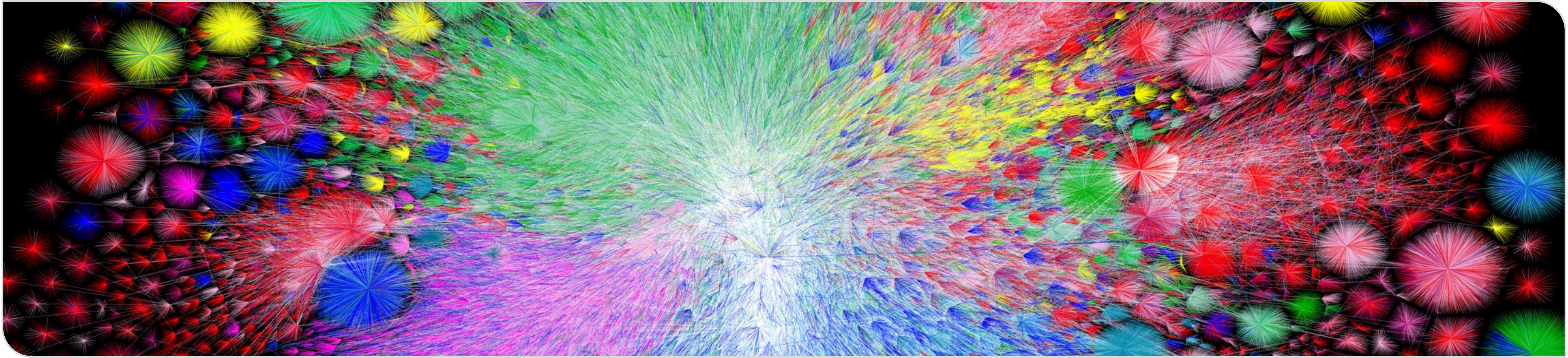
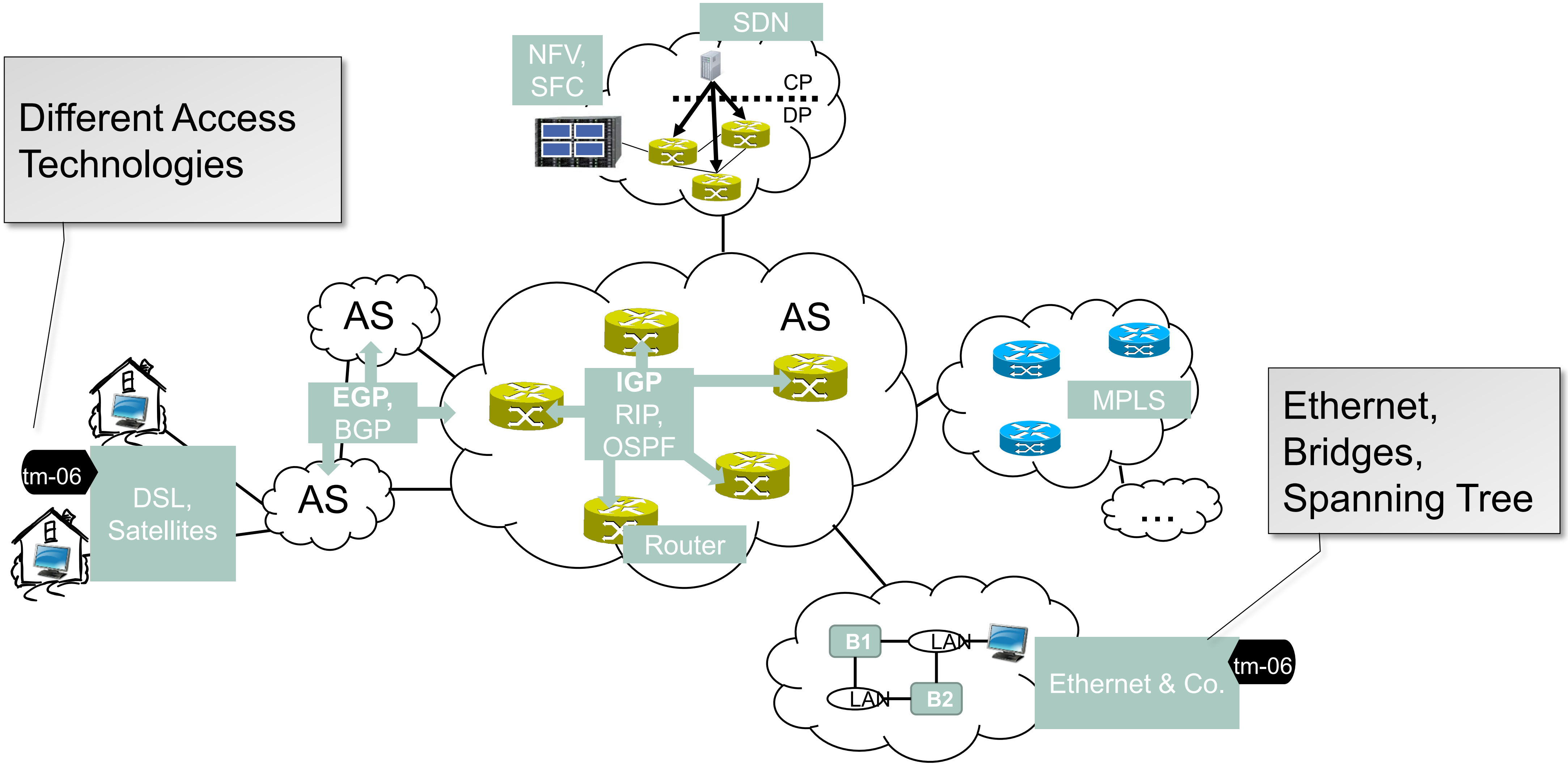
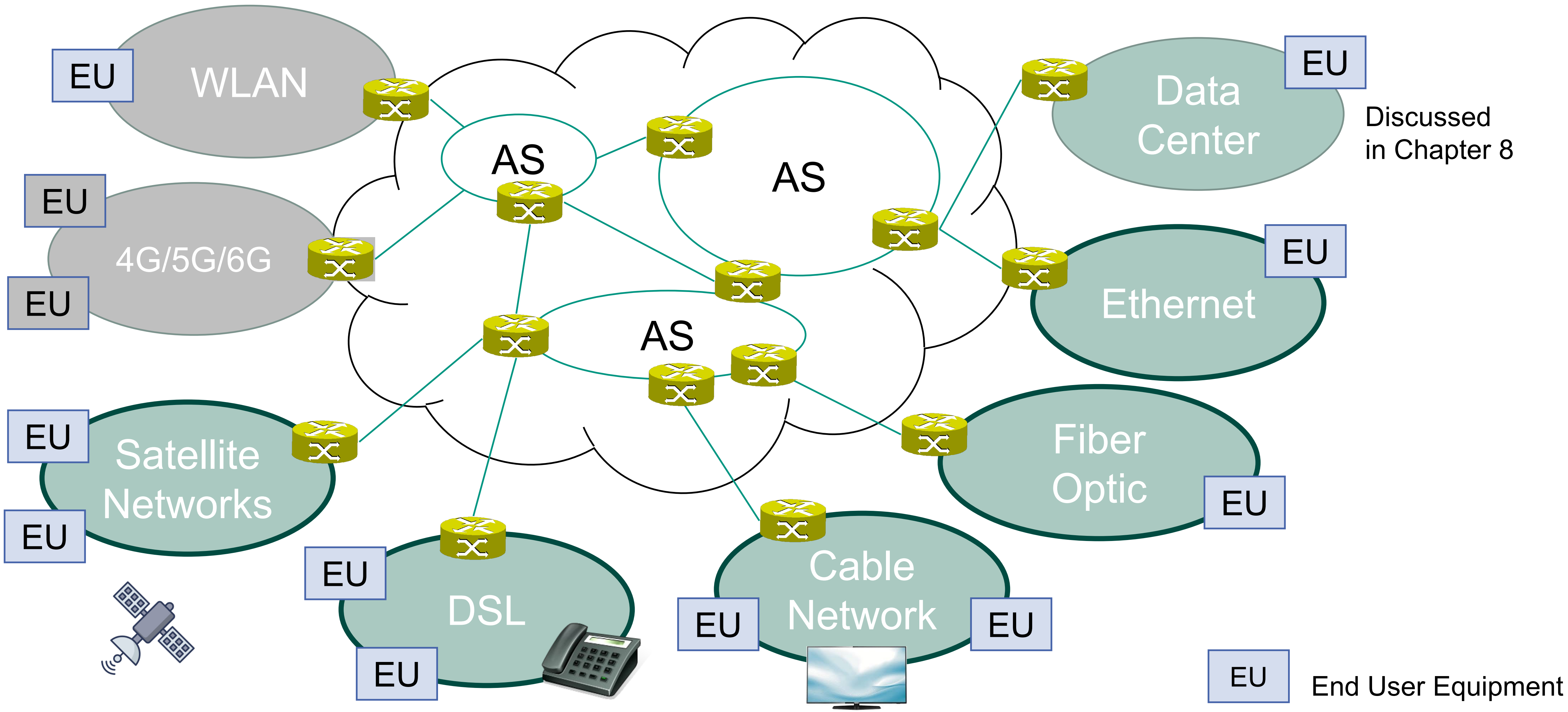



Different Access Technologies
SDN
NFV, SFC
CP
DP
AS
AS
AS
EGP, BGP
IGP
RIP, OSPF
Router
MPLS
...
tm-06
DSL, Satellites
B1
LAN
LAN
B2
Ethernet & Co.
tm-06
Ethernet, Bridges, Spanning Tree

Access Networks



6

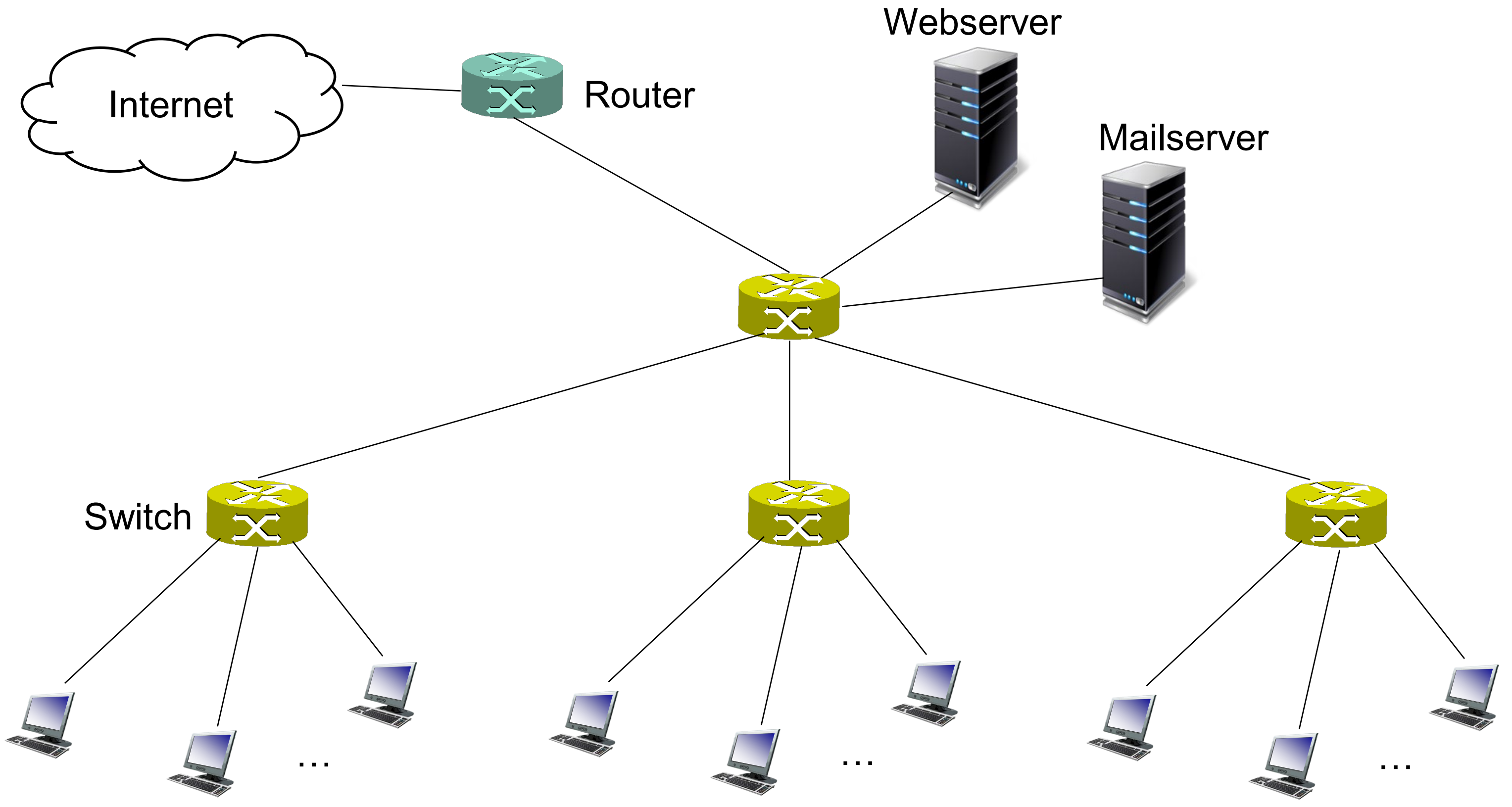
Access Networks

6.1 Ethernet

6.1.1 Ethernet Segment

Switched Ethernet

- Typical local area network with switched Ethernet
  - Switches are used internally (forwarding based on MAC addresses)
  - Router attaches switched LAN to Internet (based on IP addresses)



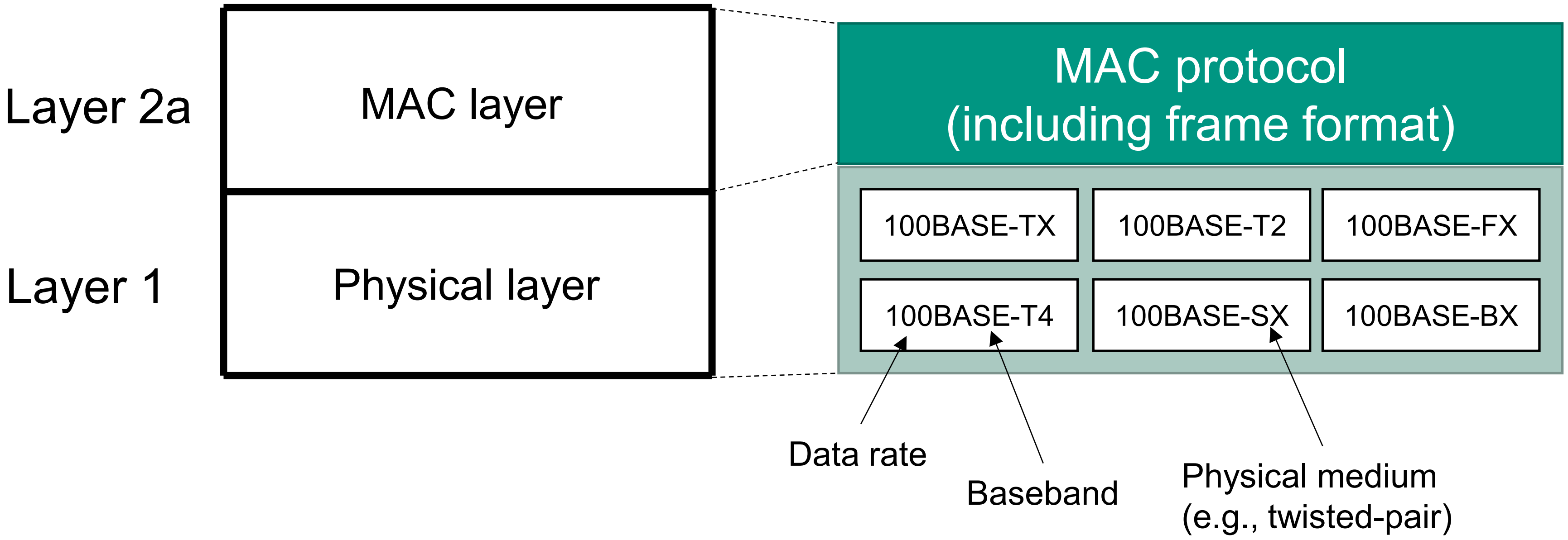
Originally Ethernet was bus-based

[KuRo21]

Ethernet Technologies

- Ethernet comprises
  - One MAC protocol and frame format
  - Many different Ethernet technologies

- Example Ethernet technologies



[KuRo21]

Medium Access Control

- Originally based on CSMA/CD
  - Carrier Sense Multiple Access with Collision Detection

- Characteristics
  - Uses time multiplexing
  - Medium access at random point in time
  - Asynchronous access without any synchronization among accessing devices

- Process
  - Sense if medium is free before starting to send
    - „Listen before talk“
  - Sending system can detect collisions by listening
    - “Listen while talk“

Ethernet Frame

min. 64 Byte (DA through FCS)

PR	SD	DA	SA	Type	Data	Pad	FCS	
(7)	(1)	(6)	(6)	(2)	(≤ 1.500)	(optional)	(4)	Byte

- PR = preamble for synchronization (1010101010...)
- SD = Start-of-frame Delimiter at beginning of frame (10101011)
- DA = Destination Address
- SA = Source Address
- Type/Length
  - Type = transported protocol
  - Length = length of the data
- Data = Transported data
- PAD = Padding
- FCS = Frame Check Sequence

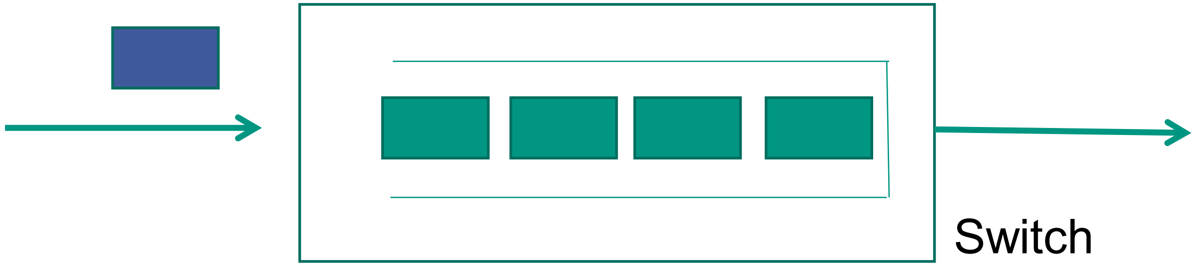
- Between two subsequent frames: IFS

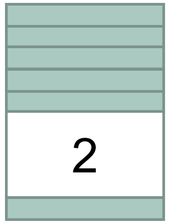
Ethernet Flow Control

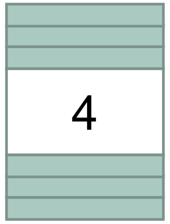
Overload in Ethernet Switches

… faster interfaces, switch as central component …

- Problem
  - Switch can become performance bottleneck
  - Frames are temporarily buffered
    - If buffer is full: frames have to be dropped







  - Ethernet normally provides unreliable best-effort service
    - Loss recovery is done at transport layer (TCP)
      - … not performant

New Mechanism added: Ethernet Flow Control

- Problem
  - Buffer overflow and, consequently, frame loss in layer 2 switches
  - Resource bottleneck should be handled there (not at layer 4)
- Goal
  - Avoid packet losses due to buffer overflow
- Approach: flow control at layer 2
  - Reduce traffic transmitted to switch
    - Deal with short-term transient overload conditions
    - → reduce traffic received from preceding neighboring switch
      - Hop-by-hop flow control - sender and receiver (at layer 2) are neighboring switches
- Solutions depends on charachteristics of link between neighboring switches
  - Half-duplex links
    - Implicit flow control
  - Full-duplex links
    - Explicit flow control

Implicit Flow Control

- Half-duplex link

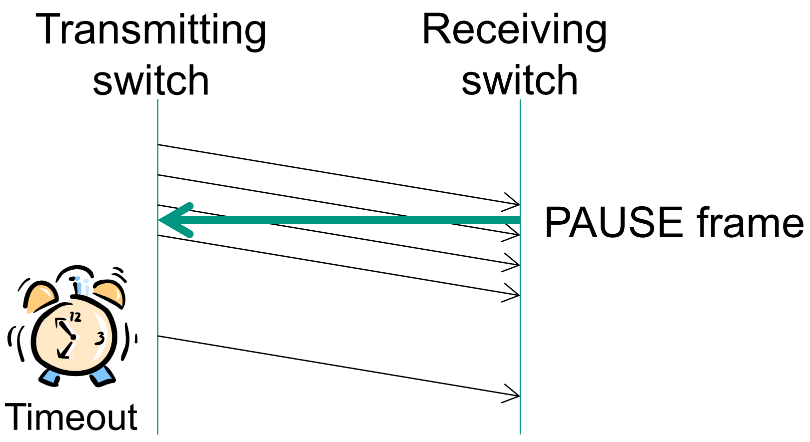
- Backpressure
  - Prevent potential transmitter from actually sending traffic

- Two backpressure methods available
  - Enforce collision
    - CSMA/CD (collision detection) notices collision
    - Sender aborts sending and repeats frame (backoff)
      - But: possibly long delay
      - What happens with 16 losses following each other?
  - Pretend medium is busy
    - Send potentially correct bit sequence (e.g., preamble)
    - CSMA/CD (carrier sense) notices busy medium
    - Sender is waiting for free medium … also increases delay

… not possible with duplex links, since no CSMA/CD is used

Explicit Flow Control

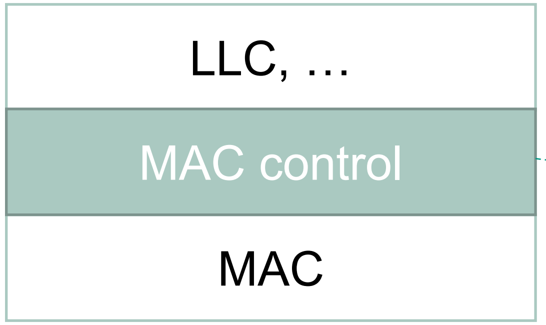
- Full duplex link
- Pause function
  - Receiver transmits PAUSE frame in case of an overload situation
  - Sender stops transmitting data frames when receiving a PAUSE frame
  - Implicit continuation after pause time given in PAUSE frame
    - Time is multiple of time for sending 512 bit
  - Explicit continuation when receiving PAUSE frame with time=0



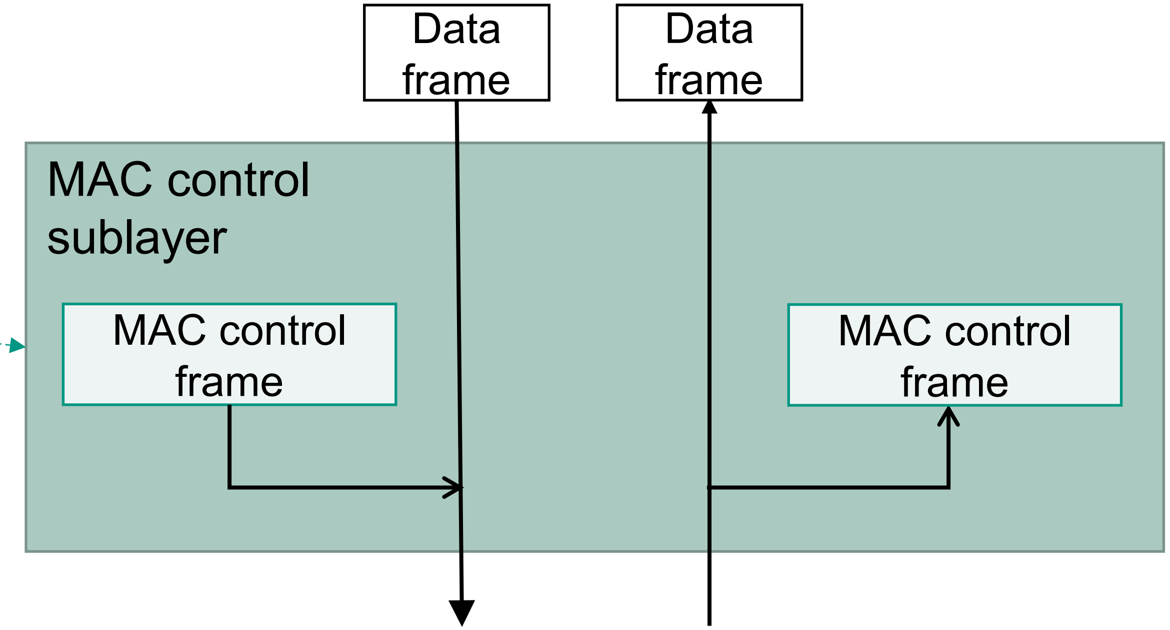
Do not delay protocols of higher layers

MAC Control Sublayer

- Extension of MAC layer
  - New sublayer: MAC control
    - Optional
    - Introduction of control frames at MAC layer (e.g., PAUSE frame)
      - Unreliable service (best-effort)
  - Sublayers of layer 2



- Handling of MAC control frames
  - Terminate at the MAC control sublayer or are generated by it
  - All other frames are passed from/to higher layers
- Schematics



MAC Control Frame

- Structure

PR (7)	SD (1)	DA (6)	SA (6)	Type (2)	MCC (2)	MAC Control Parameters (44)	FCS (4)	Byte

- Type = 0x8808
- MCC: MAC Control Opcode
  - Code for selected control function
  - 0x0001: PAUSE frame
    - Can only be used with full duplex links
    - Send to special multicast address
    - Parameter: desired pause time
- MAC Control Parameters
  - Unused part filled with zeros at the end

Coping with increasing Data Rates

Increasing Data Rates – Rough Overview

- Goal: Backward compatibility
  - Keep frame format as is
    - This comprises minimum frame size
  - Support CSMA/CD medium access

- Consequence
  - If data rate increases network size needs to be reduced
    - Otherwise CS (Carrier Sense) does not work anymore

Recall:
$t_s \geq 2 \cdot t_a$
needed

Fast Ethernet – 100 Mbit/s

- Maximum extension of Ethernet segment reduced
- Full-duplex and half-duplex links
  - CSMA/CD on half-duplex links still needed

Gigabit Ethernet – 1 Gbit/s

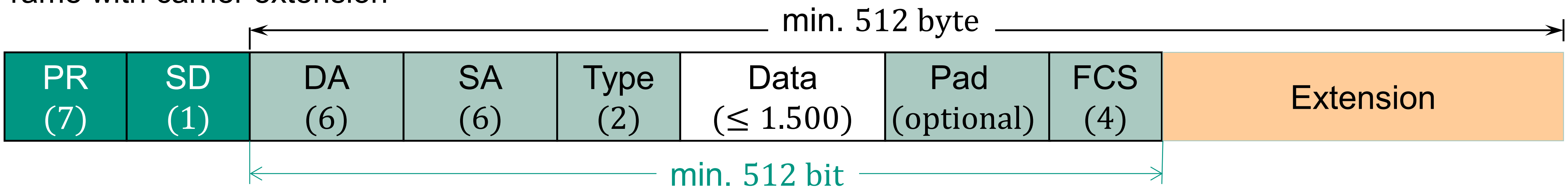
- Further reduction of segment extension not feasible
- Full-duplex and half-duplex links
  - CSMA/CD on half-duplex links still needed
- Carrier extension and frame bursting introduced

10/40/100 Gigabit Ethernet

- Only full-duplex links supported – no CSMA/CD needed
- Carrier extension and frame bursting deprecated
- Jumbo frames standardized (9014 byte payload)
- Only point-to-point connections, no broadcast medium

Carrier Extension

- Goal
  - Ensure collision detection
- Approach
  - Increase transmission delay without modifying Ethernet frame structure
- Basic enhancements
  - Length of time slot ≠ minimum length of frame
    - Minimum frame length: 512 bit
    - New length of time slot: 512 byte
  - Frame with carrier extension



- Extension: 1 – 448 bytes
  - Send as “nondata symbols” on physical layer

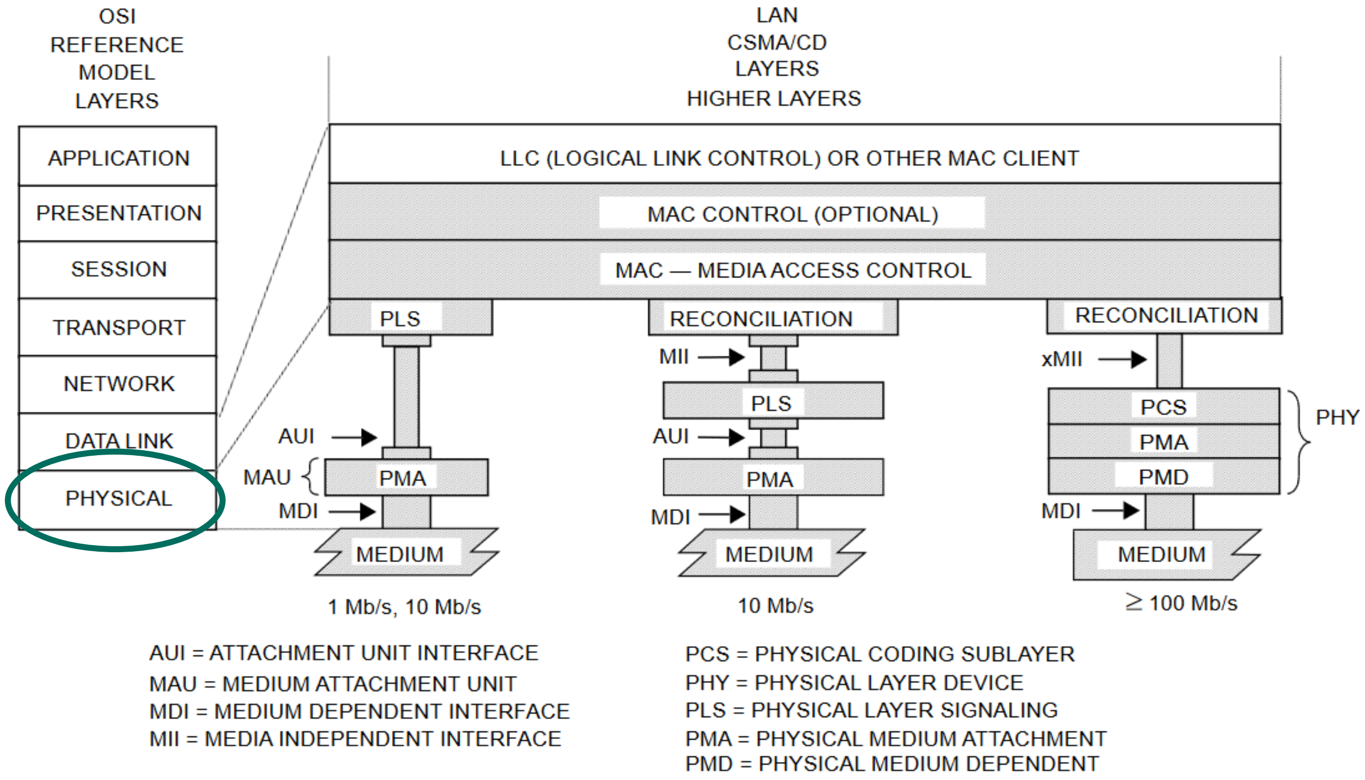
Frame Bursting

- Goal
  - Efficient transmission of short frames
- Approach
  - Devices are permitted to send burst of frames directly following each other
    - First frame with extension, if required
      - Might be required for collision detection
    - Following frames directly back-to-back (no extension)
      - Last frame has to start after at most 8192 bytes
- Schema

- P: Preamble, Start-of-Frame-Delimiter
- D: Ethernet frame
- E: Carrier extension
- I: Inter frame space

Physical Layer Specifications

- Most current advances on Ethernet take place at the physical layer
  - Composed of a set of sublayers, e.g., for 40 Gbit/s Ethernet

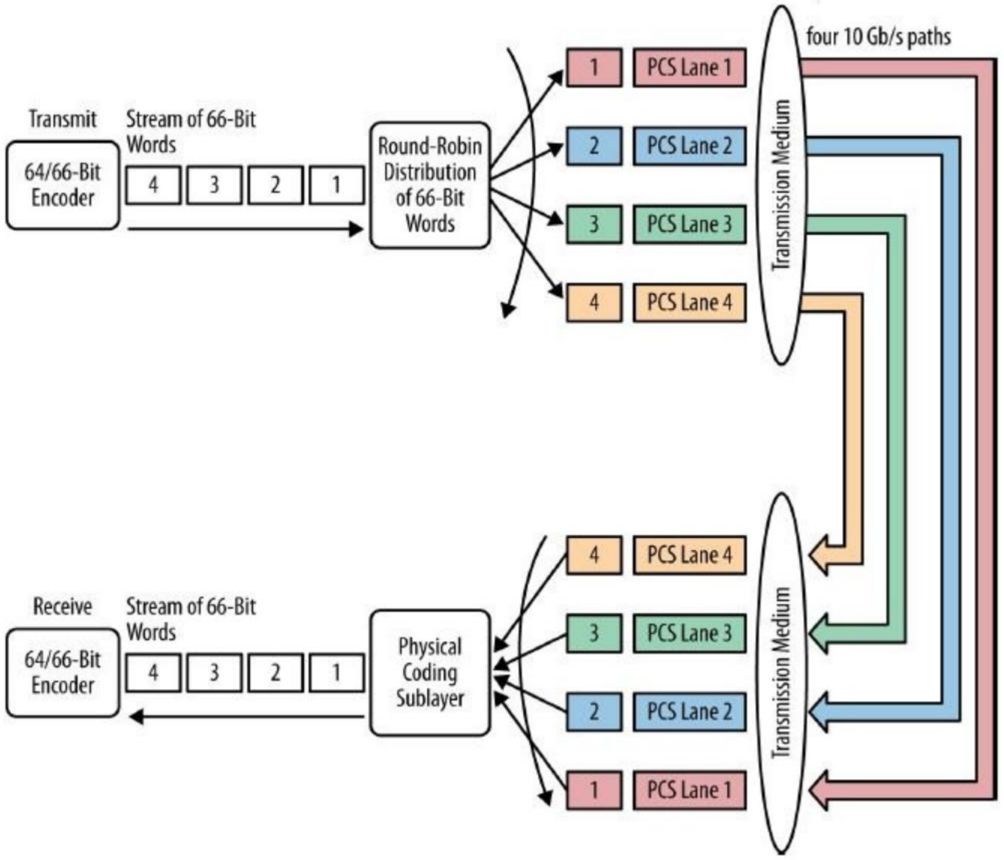


- Variety of Ethernet technologies is increasing
  - Fiber, copper cable, backplane
  - Different distances, e.g., 10 km on single mode fiber, 1 m over backplane

[Ethe18]

Multilane Distribution

- Applied for 40 Gbit/s and 100 Gbit/s Ethernet
- Concept: use multiple parallel channels
  - Multiple separate physical wires (e.g., 4 twisted-pair links) or
  - Separate frequency channels (e.g., wavelength division multiplexing)
- Example: 40 Gbit/s Ethernet



Summary Ethernet Segment

- Today´s Ethernet is very different
  from the original version developed by Metcalf and Boggs

  - Data rate has increased by four orders of magnitude
    - … and continues to increase … 400 Gbit/s, 800 Gbit/s …
  - A variety of different media is used
  - Ethernet extends to metropolitan area networks
    - Ethernet standard 2018: "… this is a standard for Local and Metropolitan Area Networks"
    - … and to wide area networks
  - Switched Ethernet is dominant
  - On point-to-point full duplex links CSMA/CD not needed
  - Flow control introduced

- One constant has remained
  - The Ethernet frame format

6.1.2 Interconnecting Multiple Ethernet Segments

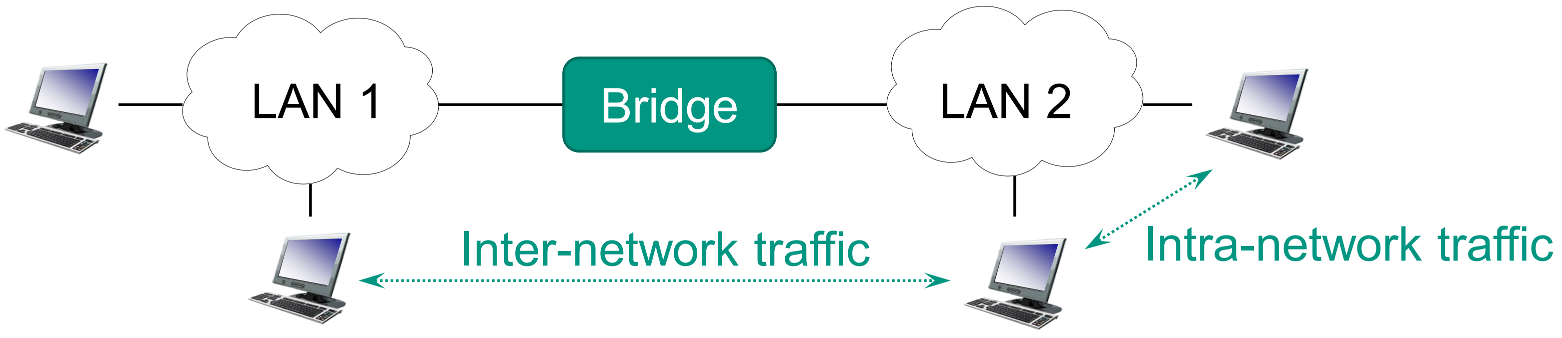
Bridges

- Goal
  - Connect local area networks (LANs) on layer 2
    - Without requiring any manual configuration (e.g., IP addresses)

- Properties
  - Filter function
    - Detaches intra-network traffic in one LAN from inter-network-traffic to other LANs

      … increases network capacity of big LANs

- Schema



Transparent Bridges

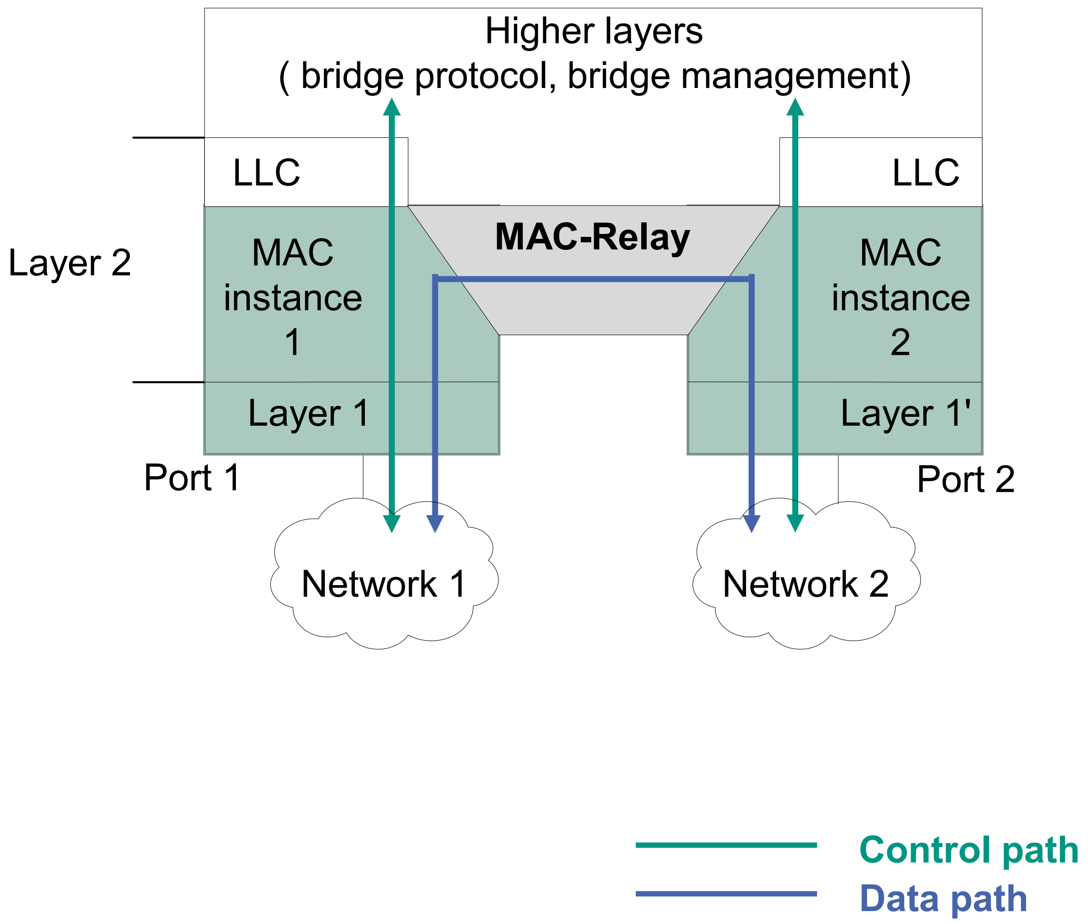
- Basic operation
  - Local forwarding decisions in each bridge
    - Forwarding information stored in a forwarding table (here at layer 2)
    - Static entries as well as dynamically learned/forgotten entries
  - End system is not involved in forwarding decisions
    - Existence of bridges is transparent to end systems
  - Often used in practice (e.g., in context of switched Ethernet)

Switches are transparent bridges with multiple ports

- Note
  - There are also Source-Routing Bridges … but not further discussed here

Transparent Bridges / Switches

- Important features
  - For each bridge port exist separate layer 1 and MAC instances
  - Data path forwarding
    - Through MAC-Relay: implements forwarding on layer 2
  - Control path
    - E.g., bridge protocol, bridge management
    - LLC instances are involved



Basic Tasks

- Establishing a loop-free topology
  - Packets must not loop endlessly in the network

  → *Rapid Spanning Tree algorithm*

- Forwarding of packets
  - Learning the “location” of end systems
    - Creation of entries in the forwarding table
  - Filtering resp. forwarding of packets
    - Based on the information in the forwarding table

Compare learning switch in chapter on programmable networks

6.2.1 Establishing Loop-Free Topology

Spanning Tree Algorithm: Standardization

- Spanning Tree Protocol (STP), IEEE 802.1d
  - … but: re-convergence quite slow, about 30-50 seconds

- Rapid Spanning Tree Protocol (RSTP), IEEE 802.1w
  - Goal: faster re-convergence times
    - … only needs a few seconds

- Since IEEE 802.1d-2004
  - RSTP is part of the standard, original STP is obsolete

- IEEE 802.1q-2022
  - Incorporates many additional protocols, for example
    - Multiple Spanning Tree Algorithm and Protocol (MSTP)
    - Shortest Path Bridging (SPB)

Rapid Spanning Tree Protocol (RSTP)

- Task
  - Organize bridges in a tree topology through which all end systems can be reached
    → No loops possible
    - Network modelled as graph
      - Nodes: bridges/switches and local networks
      - Edges: connections between bridge ports and local networks
  - *… not all bridges or bridge ports in the network have to be part of the tree topology*
    - → resources might not be used optimally, but loops are avoided
- Forwarding of packets
  - Only possible along the established tree

An earlier version was called STP: Spanning Tree Protocol. It reacted slower to changes.

Radia Perlman … Algorhyme

I think that I shall never see
A graph more lovely than a tree.

A tree whose crucial property
Is loop-free connectivity.

A tree that must be sure to span
So packets can reach every LAN.

First, the root must be selected.
By ID, it is elected.

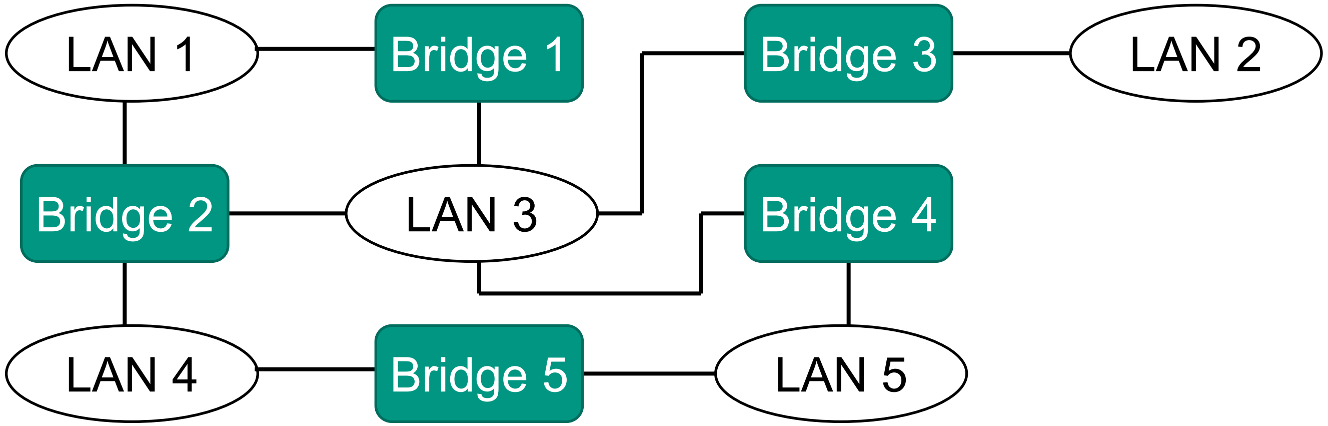
Least cost paths from root are traced.
In the tree, these paths are placed.

A mesh is made by folks like me,
Then bridges find a spanning tree.

[Perl92]

Example Network and Requirements

- Example network



- Requirements for using RSTP
  - Group address to address all bridges in the network (MAC address!)
  - Unique bridge identifier per bridge in the network
  - Unique port identifier per port in each bridge
  - Path costs for all ports of a bridge have to be known

Bridge Protocol Data Units (BPDUs)

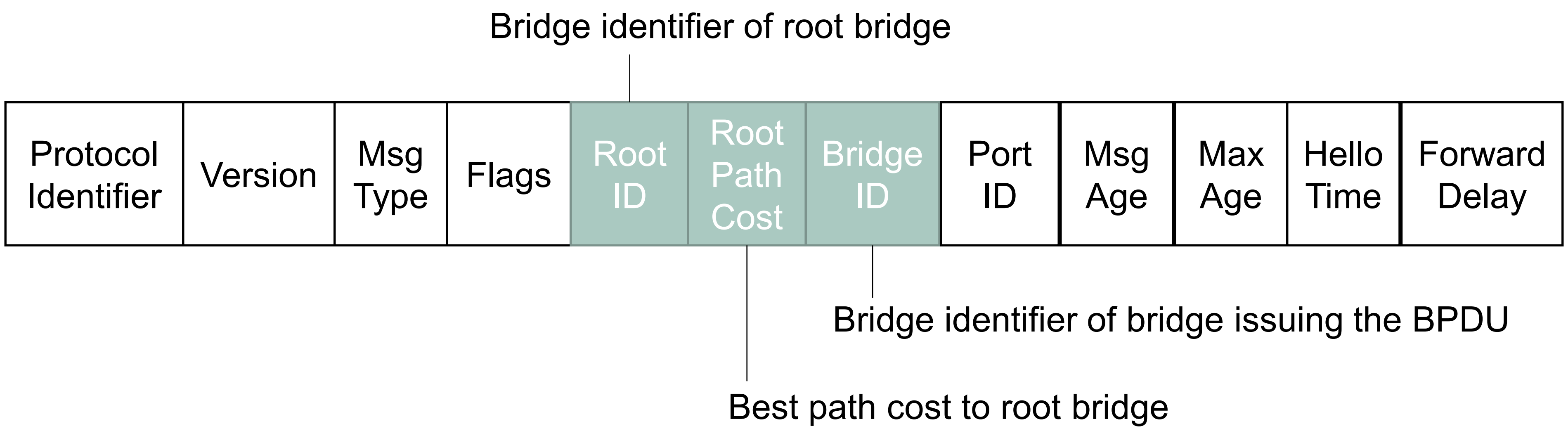
- Bridges send special control packets: Bridge Protocol Data Units (BPDUs)
  - BPDU contains (among others)
    - Bridge identifier of bridge that issues BPDU
    - Bridge identifier of bridge that is currently assumed as root bridge
    - Path cost from bridge issuing the BPDU to root bridge

Bridge Identifier

- Bridge identifier
  - Consists of a priority field and of a MAC address
    - Priority is a configuration parameter
      - Default Value: 32768
    - MAC address ensures uniqueness
      - Each port has a unique MAC address

Priority	MAC address
2 byte	6 byte

Format of a BPDU



- Exchange of BPDUs in order to configure the spanning tree, i.e.,
  - Electing the root bridge
  - Determining port roles and states
  - Blocking unwanted ports

Basic Steps of RSTP

1) Determine root bridge

2) Determine root port for each bridge
   - Calculate path costs to the root bridge
     - Sum over costs of all hops on path to the root bridge
       - Metric: e.g., according to data rate of connected links
   - Select port with lowest costs

Port roles

Root port

Basic Steps of RSTP

Karlsruher Institut für Technologie

3) Determine designated bridge for each LAN (loop free!)

- LAN can have multiple bridges
- Select bridge with lowest costs on root port
  - Called designated bridge
  - Resolve equal costs over bridge identifier
- Responsible for forwarding of packets
- Other bridges in the LAN will be deactivated
  - Affected ports become alternate ports or backup ports
  - Alternate ports and backup ports are in blocking state

Port roles

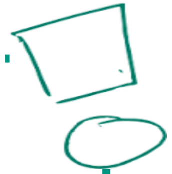
- Alternate port
  - Best alternative port to root bridge
  - Will take over if current root port fails
- Backup port
  - Alternative path to a network that already has a connection
    - Bridge has two ports which connect to same network

Alternate port

Backup port

Rapid Spanning Tree Protocol: BPDUs

- Initially
  - Bridges have no topology information
  - All bridges assume: “I am the root bridge”
    - Periodically send BPDU which announces itself as root bridge
    - Bridges only forward BPDUs, no “normal” frames
- Receiving BPDU with smaller bridge identifier
  - Bridge no longer assumes that it is the root bridge



> Bridge with smallest bridge identifier will become root bridge

- When receiving BPDU possibly update of the configuration
  - BPDU contains root bridge with smaller identifier → new root bridge learned
  - BPDU with same root bridge identifier but cheaper path to root bridge → better path learned
  - Bridge notices that it is not the designated bridge
    - No longer forwards BPDUs

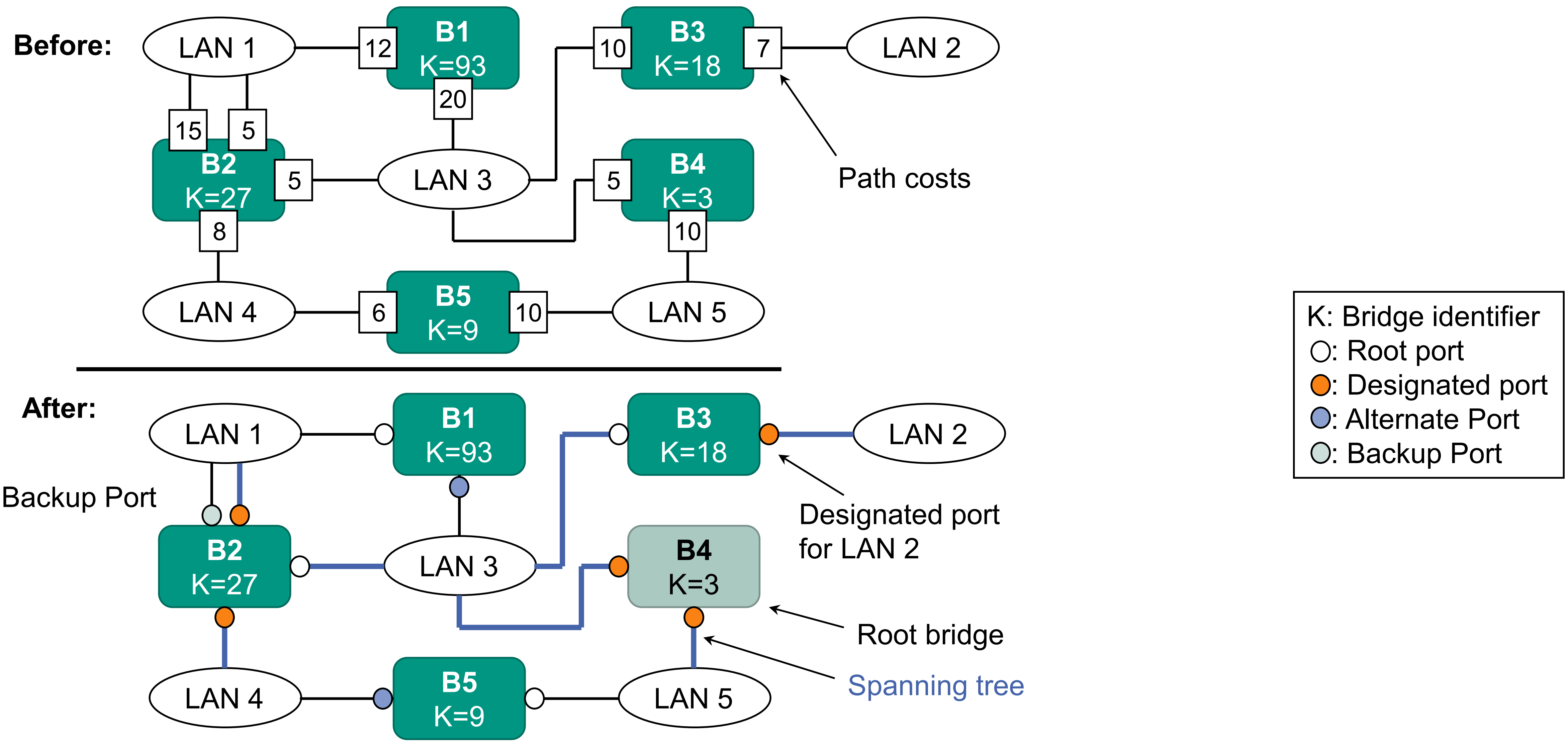
Rapid Spanning Tree Protocol: Stable Phase

- Every bridge periodically sends BPDUs (Hello-Timer = 2s)
  - To the next hierarchy level in the tree
  - BPDUs forwarded on designated ports
  - Used as keep-alive mechanism between bridges

- Not received BPDU on a given port for three consecutive times
  - Connectivity to neighbor is considered as lost
  - Protocol information is immediately aged out
  - Bridge again assumes that it is the root bridge
    - Sends corresponding BPDUs
    - Algorithm re-starts

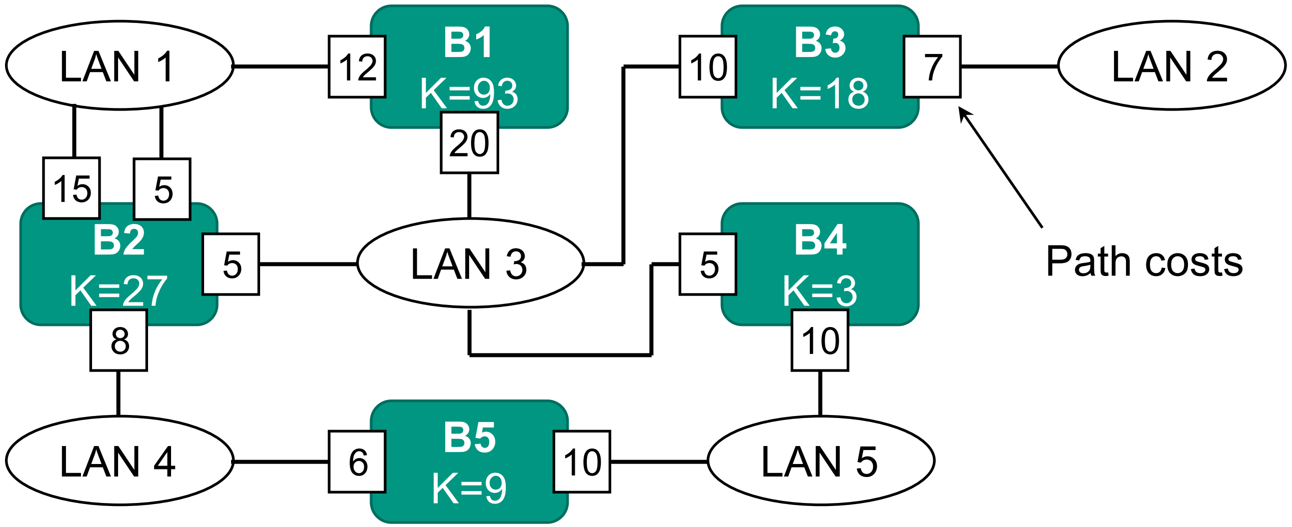
- After stabilization frames are forwarded over respective ports
  - Based on entries in the forwarding table

Example


Before:
LAN 1
12
B1
K=93
20
10
B3
K=18
7
LAN 2
15
5
B2
K=27
5
LAN 3
5
B4
K=3
8
10
Path costs
LAN 4
6
B5
K=9
10
LAN 5
After:
LAN 1
B1
K=93
B3
K=18
LAN 2
Backup Port
Designated port
for LAN 2
B2
K=27
LAN 3
B4
K=3
Root bridge
Spanning tree
LAN 4
B5
K=9
LAN 5
K: Bridge identifier
: Root port
: Designated port
: Alternate Port
: Backup Port

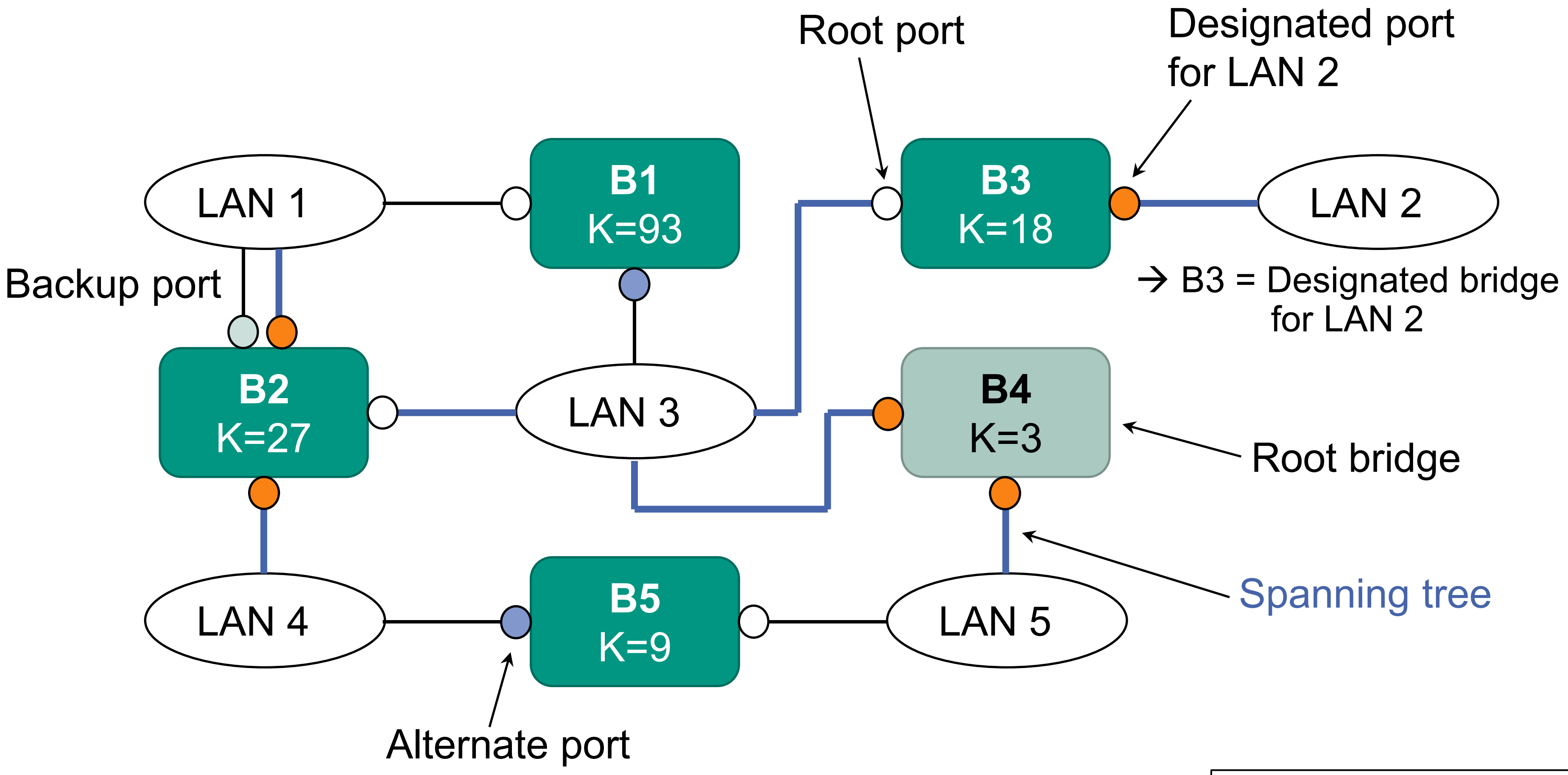
Calculate Path Costs to Root Bridge

Before:



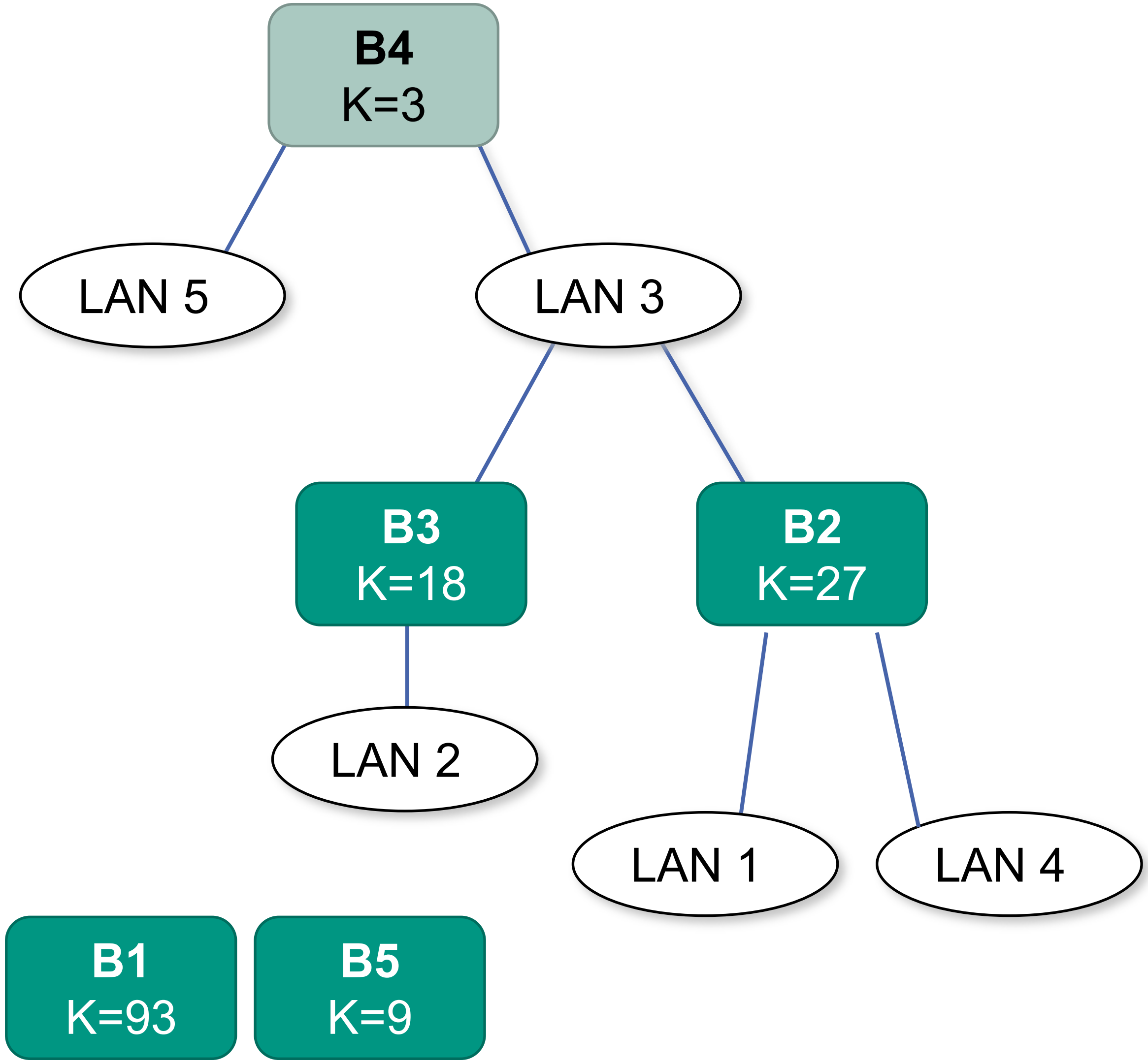
Bridge	Path costs to root bridge
B3	**10** (via LAN 3)
B1	20 (via LAN 3)
	17 = 12 + 5 (via LAN 1 & LAN 3)
B2	**5** (via LAN 3)
	18 = 8 + 10 (via LAN 4 & LAN 5)
	25 = 5 + 20 (via LAN 1 & LAN 3)
	35 = 15 + 20 (via LAN 1 & LAN 3)
B5	**10** (via LAN 5)
	11 = 6 + 5 (via LAN 4 und LAN 3)

Determine Designated Bridges



1 root port per bridge (except root bridge)
1 designated port per LAN

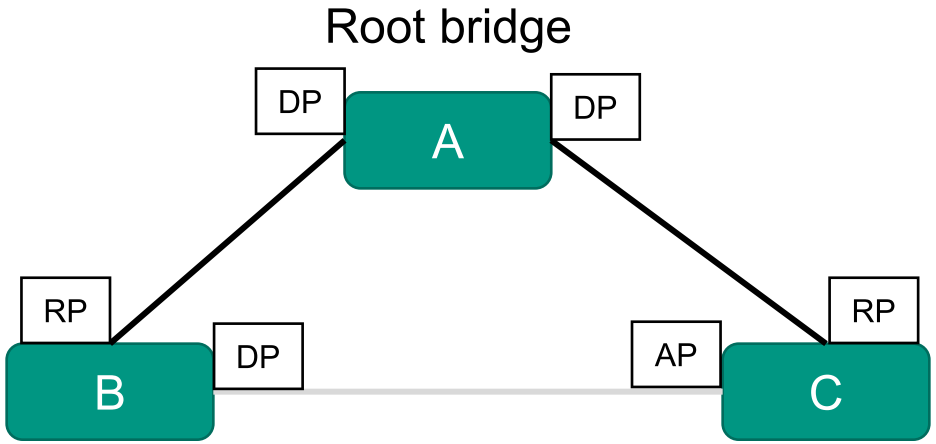
Resulting Spanning Tree



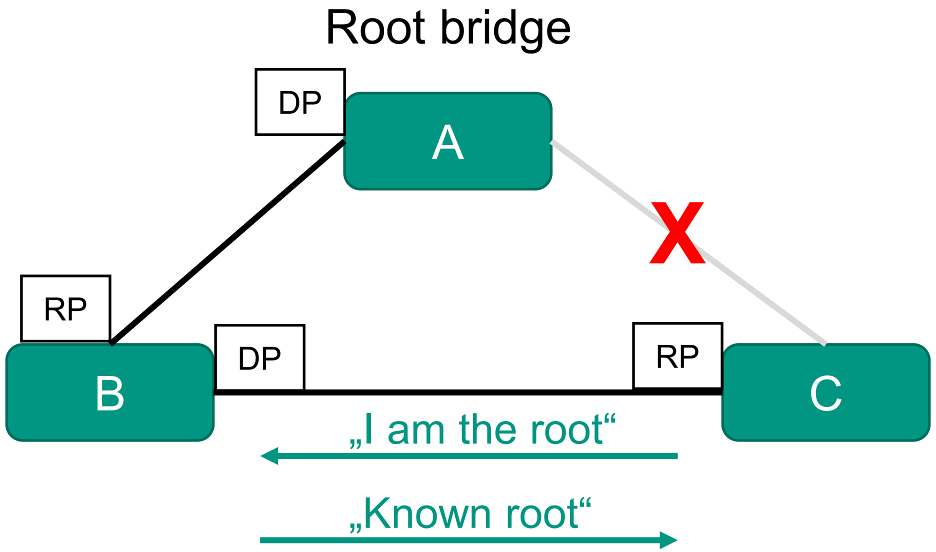
LAN	Designated bridge
LAN 1	B2
LAN 4	B2
LAN 2	B3
LAN 3	B4 (Root bridge)
LAN 5	B4 (Root bridge)
---	B5
---	B1

Accepting Inferior BPDUs: Simple Example

- Established spanning tree
  - Link B-C is not part of spanning tree

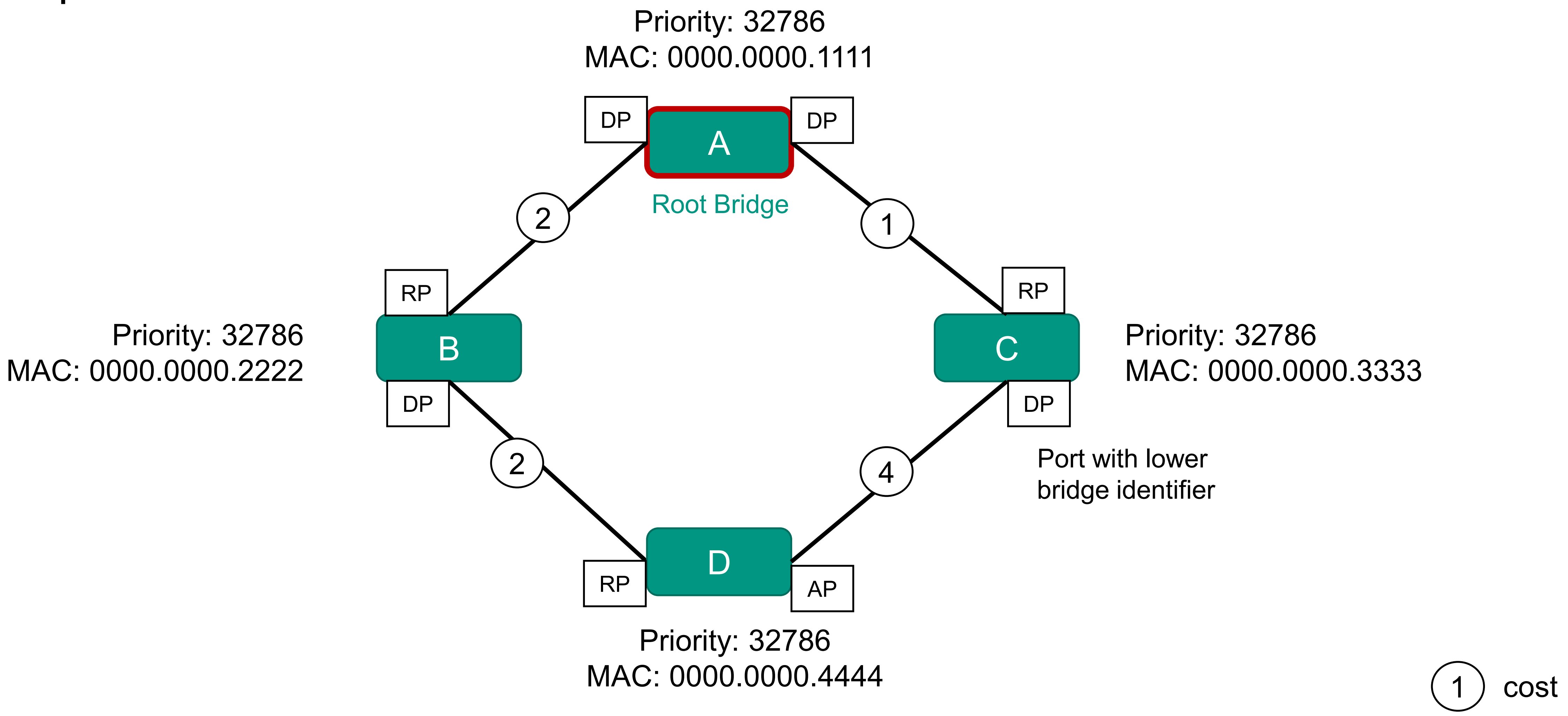


- Link A-C fails
  - Switch C does not receive BPDUs from A
  - C assumes it is the new root bridge
  - C sends BPDU „I am the root“ to switch B
  - B knows root bridge is still alive
  - B sends BPDU “known root” to C
    - Contains root bridge identifier
  - Switch C sets root port accordingly
  - Note: root bridge not involved
    - Local recovery



Pure Switched Ethernet Networks

- Example switched network



6.2.2 Frame Forwarding

Forwarding of Frames

- Forwarding table
  - Static and dynamic entries
    - Static entries: created by network administrator
    - Dynamic entries: learn/forget while operating
      - Learning through incoming packets
      - Forgetting based on timer (soft-state)
  - Entries contain information required for forwarding
    - Destination address, outgoing port and ageing time
      - Default value for ageing time: 300 s

SDN: proactive rules

SDN: reactive rules

- Filtering
  - Packets with local destinations are not forwarded over the bridge

  → Separate traffic from different LANs to increase scalability

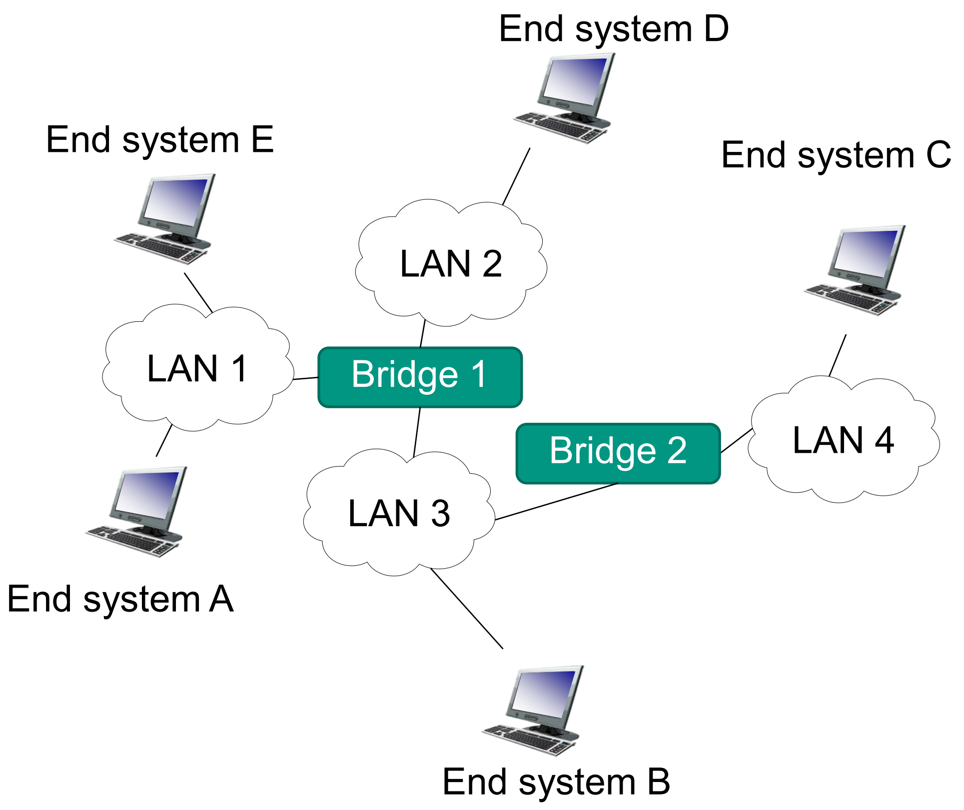
Forwarding of Frames

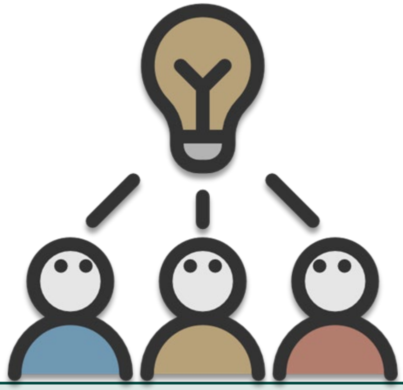
- Bridge receives a frame on input port
  - Destination known
    - Destination identified by destination MAC address in the frame
    - Matching entry exists in forwarding table
    - Forward frame over respective port
  - Destination unknown
    - Flood frame
      - Send on all ports (except input port)
  - Learn "location" of the source system
    - Identified by source MAC address in the frame
    - Create new dynamic entry in forwarding table if source not yet known
      - Source system is reachable over input port

Example

- Assumption: bridge just started
  - Tree topology is established
  - Forwarding table is empty

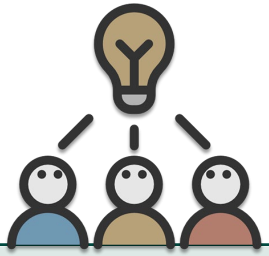
- Examples
  - A sends frame to C
    - Bridge 1 receives the frame
      - Learns that A is reachable through input port
        - New entry in forwarding table created
    - Bridge 1 does not know about C
      - Flood frame on all ports (except input port)
  - D sends frame to A
    - Bridge 1 receives frame
      - Learns “location” of D
        - New entry in forwarding table created
      - Finds information about A in forwarding table
        - Forwards frame over respective output port





Task 06-1

Why we need a spanning tree



Task 06-1

Homework

Homework 06-01

Spanning tree

6.2.3 Handling Topology Changes

BPDU

Protocol Identifier	Version	BPDU Type	Flags	Root ID	Root Path Cost	Bridge ID	Port ID	Msg Age	Max Age	Hello Time	Forward Delay

- Protocol identifier
  - 0x0000 0000 0000 0000
- Version
  - 0x0000 0010 for RSTP
- Message type
  - Only 0x0000 0010 for RSTP BPDUs
- Flags
  - Signal Topology Change (TC) or Topology Change Acknowledgement (TCA)
  - Proposal
  - Port roles, Agreement …
- Port identifier
  - Port priority : port number
- Message age
  - Time elapsed since root bridge issued BPDU
  - … measured in hops (compare TTL)
- Maximum age
  - Indicates when BDPU should be discarded
  - Default: 20 seconds
  - Limits number of bridges that can be traversed
- Hello time
  - Every hello time bridges issue BPDUs
  - Default: 2 seconds
- Forward delay
  - How long switch should wait before transitioning to a new state
  - Default: 15 seconds

Port States

Forwarding	Processing BDPUs, receive/forward frames
Learning	Learning MAC addresses, not receiving/forwarding frames
Discarding	Receiving but dropping any BPDUs

- Root ports and designated ports are in forwarding state
- Alternate ports and backup ports are in discarding state

In stable phase

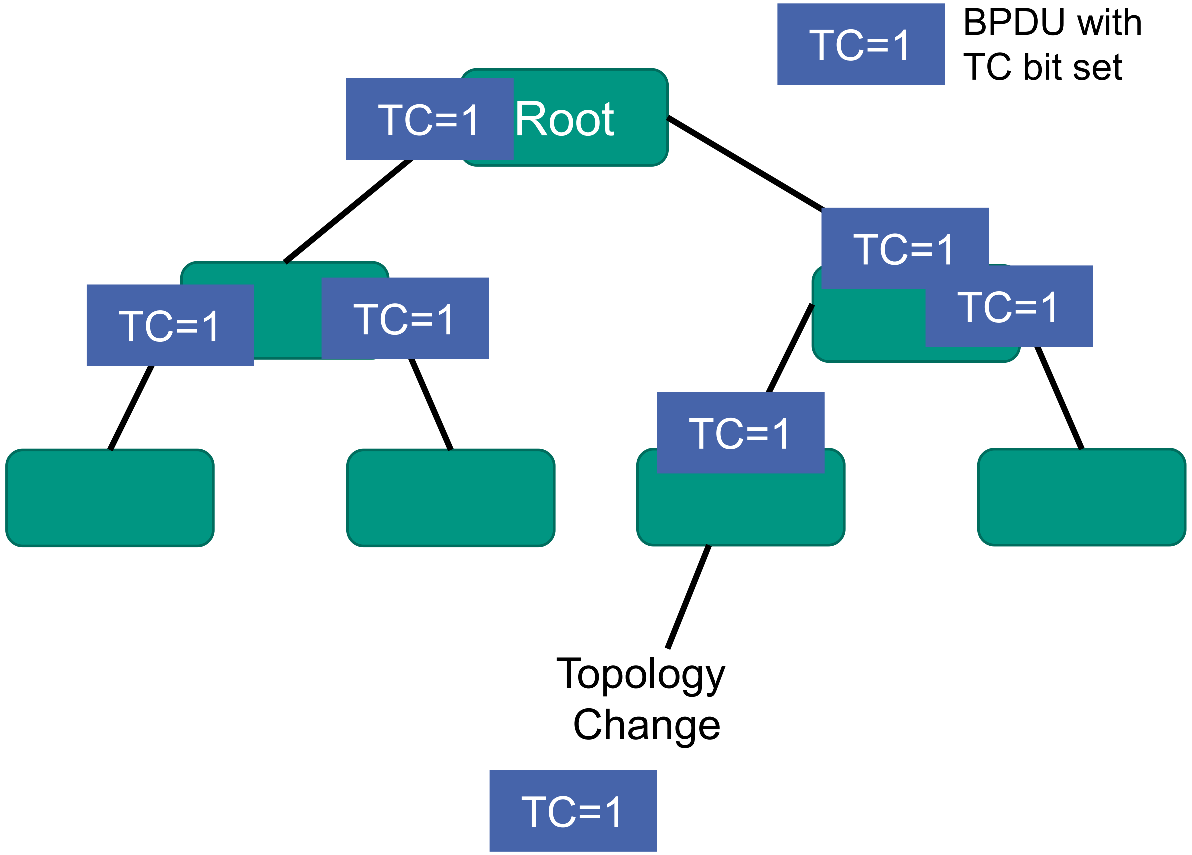
- Learning state is temporary and implements transition from discarding to forwarding state
  - For backward compatibility, only needed for half-duplex links

Topology Change (TC) Detection

- Topology change
  - Caused by non-edge port that moves to forwarding state
    - E.g., adding a new link
- Note: loss of connectivity
  - Not considered as topology change
- Bridge that detects topology change
  - Starts TC While timer for all its non-edge designated ports and its root port
    - Twice the hello time
  - Deletes MAC addresses associated with these ports
- As long as TC While timer runs at a port
  - TC bit set in all BPDUs sent out at this port
  - BPDUs are also sent on the root port

Topology Change Propagation

- Bridge receives BPDU with TC bit set
  - Deletes MAC addresses on all ports except the one where it received the topology change
  - Starts TC While timer …
- → originator of change floods this into the network
  - May result in more temporary flooding
  - But clears state information rapidly



RSTP Convergence

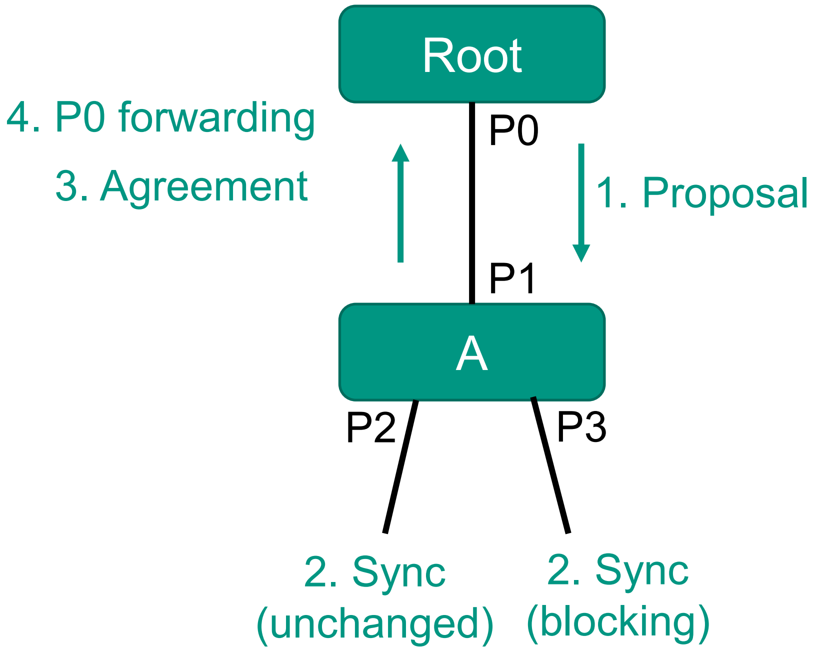
- RSTP converges much faster into stable, loop-free topology as the original spanning tree protocol (STP)
  - STP was timer-based and needed around 30-50s to converge
  - RSTP uses Proposal/Agreement-Handshakes among neighboring bridges
    - Leads to convergene in few milliseconds to seconds
    - Used to quickly synchronize changes of the local root bridge information with the rest of the topology

Proposal/Agreement Handshake: Example

- Assumption: new link created between root and switch A
  - Ports P0 and P1 are set to designated blocking state
    - → Proposal bit is set in BPDUs that are sent

- Handshake
  1. Proposal: set port P0 to forwarding state
     - Switch A receives superior information and knows that P1 is new root port
     - A starts Sync to verify that all its ports are in-synch with this information
  2. Synchronization
     - A blocks designated ports, here P3
  3. Agreement
     - All of A´s ports are now in sync
     - A can unblock its new root port P1 → forwarding
     - Sends Agreement BPDU to root
       - Copy of Proposal BPDU with agreement bit set
  4. Forwarding
     - After receipt of agreement, root sets P0 to forwarding
     - Now P3 is in same state as P0 before …
  - … next handshake takes place between A and neigboring switch at P3 (downstream)

- Network example



P0: designated port
P1: new root port
P2: alternate port
P3: designated port

[C-RSTP]

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6.2 DSL

6.2.0 Preamble

In the Following Sections

Wired Access

6.2	DSL
6.3	Cable Network
6.4	Fiber Optic

- Primarily for home access or small business
  - Which infrastructure used?
  - How close to the end users are fiber optics used?
  - How many end users compete on a shared medium?
  - Which data rates are supported/guaranteed?

Wireless Access

6.5	Satellite Networks

- LEO satellites can be an alternative for end users
  - Especially in areas where wired access is problematic

6.2.1 Basics

Digital Subscriber Line (DSL)

- 1999: start of Digital Subscriber Line (DSL) technology in Germany
  - 768 kbit/s data rate (in parallel to telephone service)

- Goal
  - Performant solution for subscriber connection
  - Support data services with higher data rates
    - Compared to what was there before … data rates are increasing over the years

- Different variants exist, e.g.,
  - ADSL2 and VDSL2

- “Invariant”
  - Last “mile” of connection to customer premise: copper twin conducter
    - Especially with VDSL “last mile” gets shorter

Basic Categories

- ADSL (Asymmetric DSL)
  - Follows the typical communication model of the WWW
    - A lot of data is received from the server
    - Much less own data is send to the server
  - Downstream and upstream data rates are asymmetric
    - Downstream
      - From server to subscriber: 768 kbit/s – 8 Mbit/s
    - Upstream
      - From subscriber to server: 128 kbit/s – 576 kbit/s

… in Germany mostly just called DSL

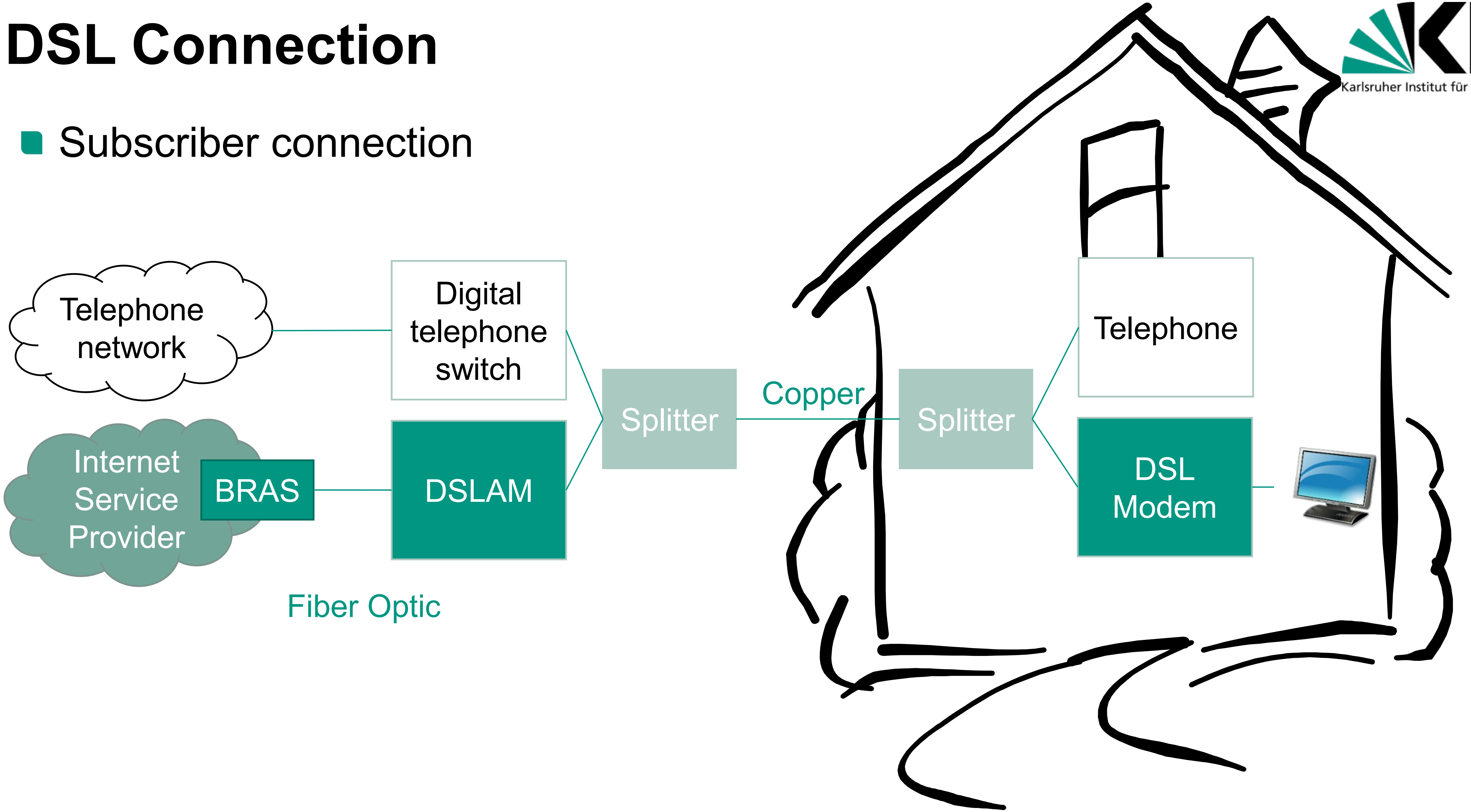
- SDSL (Symmetric DSL)
  - Mainly used by business customers
    - SDSL dedicated line. Typically with 2 – 40 Mbit/s
  - Most often much more expensive than ADSL
  - Symmetric data rate in both directions

… not discussed in the following

[ITU99]

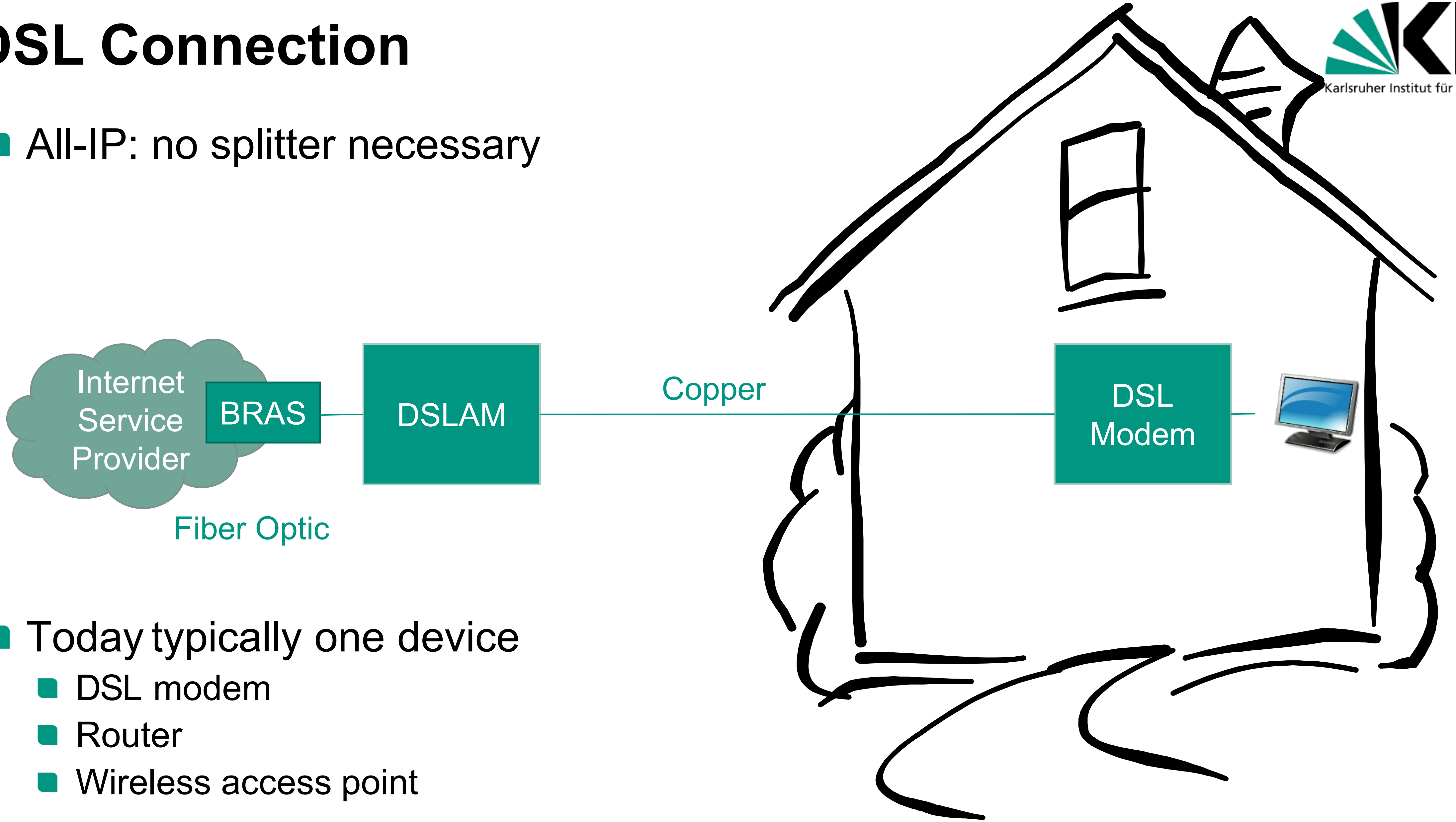
DSL Connection

- Subscriber connection



DSL Connection

- All-IP: no splitter necessary



- Today typically one device
  - DSL modem
  - Router
  - Wireless access point

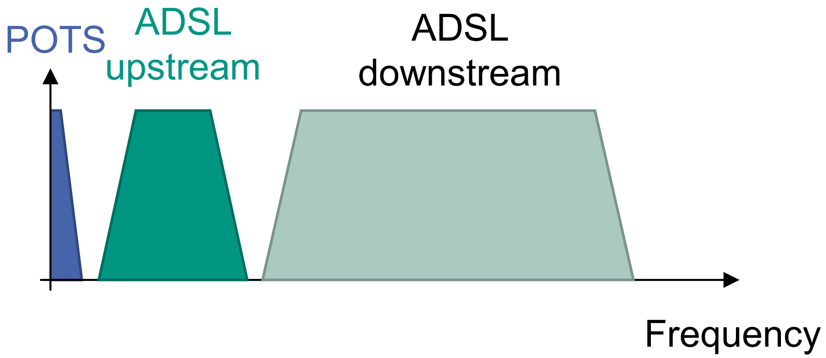
Components

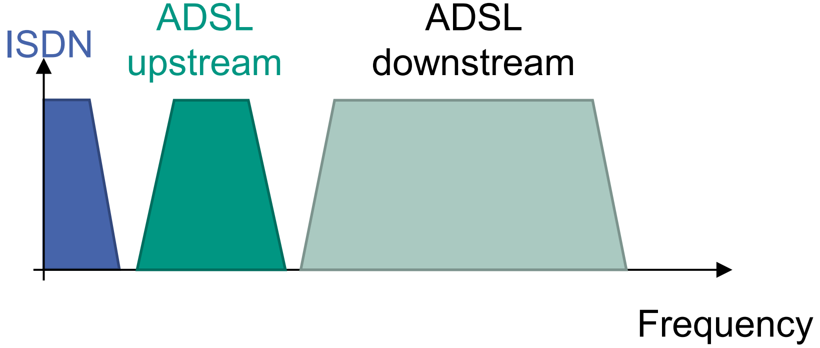
- Splitter
  - Separates signal in telephone and data signal
    - Not needed anymore in case of All-IP
- Copper twin conductor
  - Between splitters at subscriber and telephone switch
    - In case of All-IP between DSLAM and DSL modem
- DSLAM: DSL Access Multiplexer
  - Counterpart to DSL modem at subscriber
- BRAS: Broadband Remote Access Server
  - Part of the ISPs core network
  - Routes traffic to/from broadband access devices (e.g., DSLAM)
  - Aggregates traffic of multiple DSLAMs
  - Can support policy management, quality-of-service
  - Provides layer-2-connectivity and layer-3-connectivity

6.2.2 Data Transmission at DSL Access

Frequency Multiplexing

- Different frequencies for
  - Telephony
    - Use lower frequencies: 0 – 138 kHz
    - 3 kHz required for analog telephones (POTS)
    - 120 kHz required for ISDN telephones
      - Then maximum downstream only 6 Mbit/s instead of 8 Mbit/s
  - DSL upstream
    - 138-276 kHz
  - DSL downstream
    - 276-1104 kHz





DMT: Discrete Multitone Modulation

- Partition frequencies into 256 carriers à 4,3125 kHz
  - Telephony: carrier 1-31
  - DSL uplink: carrier 32-64
  - DSL downlink: carrier 65-256
  - Pilot tone: carrier 65

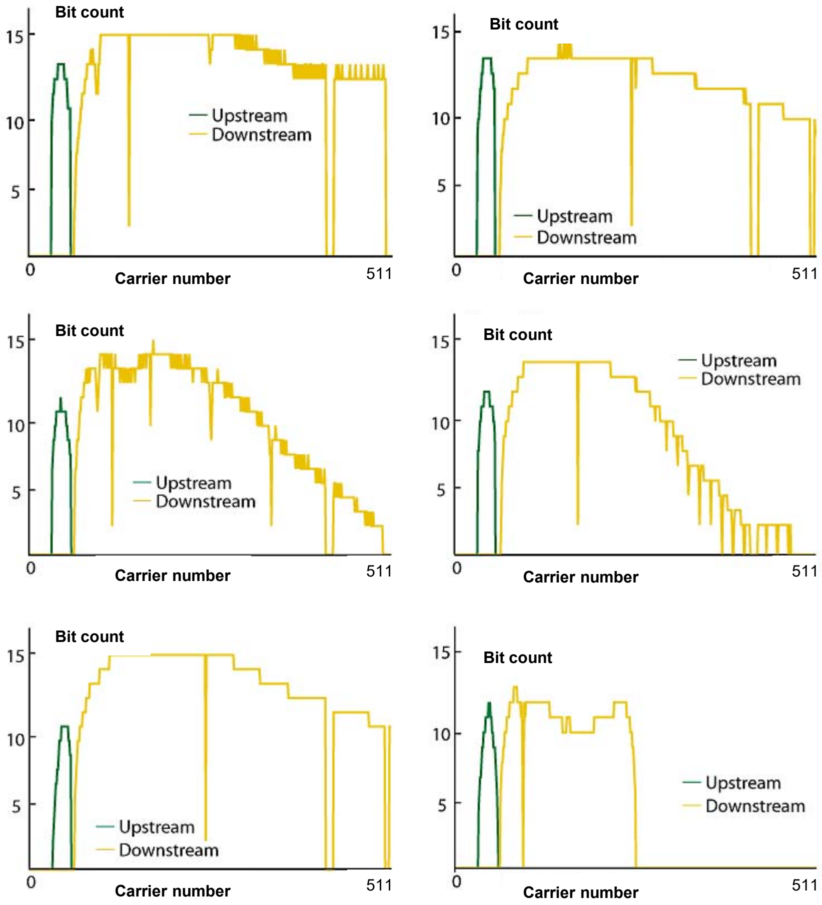
- Approach
  - Parallel transmissions on multiple orthogonal carriers with low data rate on each of them
    - See also OFDM MK

- Flexible use of carriers
  - Number of bits per link varies
    - Higher frequencies more prone to interference
    - Number of bits varies between 2 and 15, dynamically selectable

- Uses quadrature amplitude modulation (QAM) MK

Measuring Out the Carriers

- Measure out the number of transmitted bits per carrier while setting up the connection by the example of different ADSL2+ modems
  - Each carrier is measured and (theoretically) optimally used
  - ADSL2+: measuring while the connection in use is possible
  - Real examples:



- ADSL2+:
  24 Mbit/s ↓
  1 Mbit/s ↑
- Practically around 16 Mbit/s ↓ possible

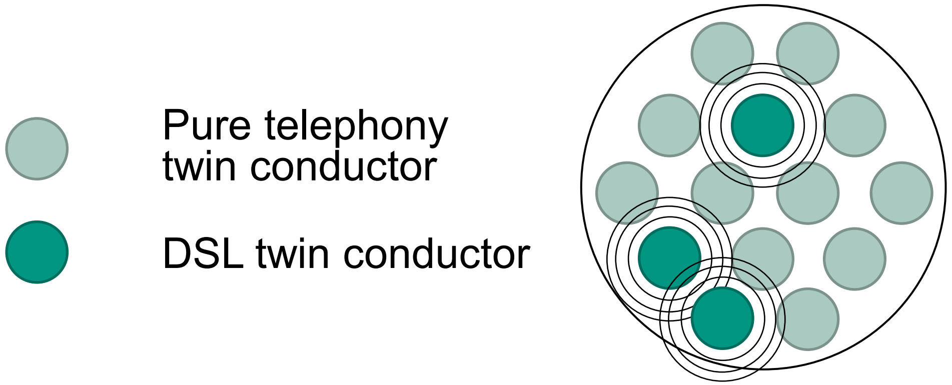
[ZiEA06]

Sources of Signal Disturbance

- Damping: primary influenced by three parameters
  - Distance, interference, cable diameter
    - Damping decreases with increasing cable diameter
    - → Larger diameter permits higher data rates on same distance

- Crosstalk
  - Interference between sender and receiver
  - Interference between senders

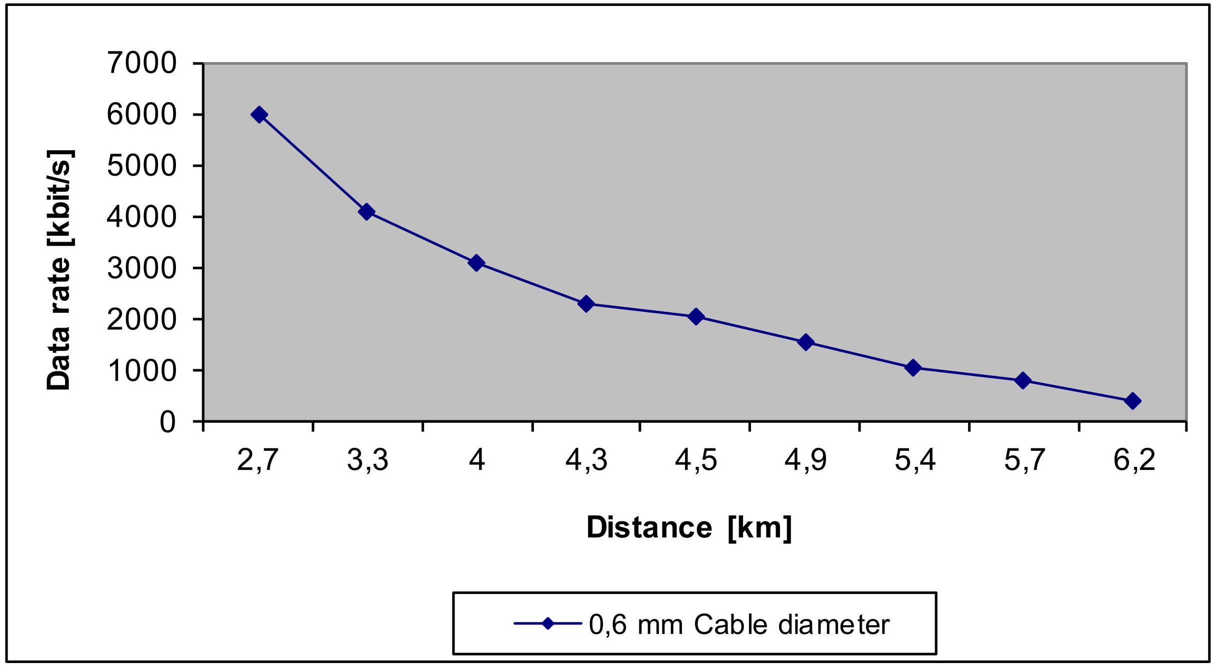
  → Only some twin conductors of a cable bundle can be used for ADSL



Damping – Distance

- Here distance between user and DSLAM
  - i.e., length of the copper twin conductor

- Properties
  - With higher distance the possible data rate decreases
  - Example: cable diameter of 0.6mm

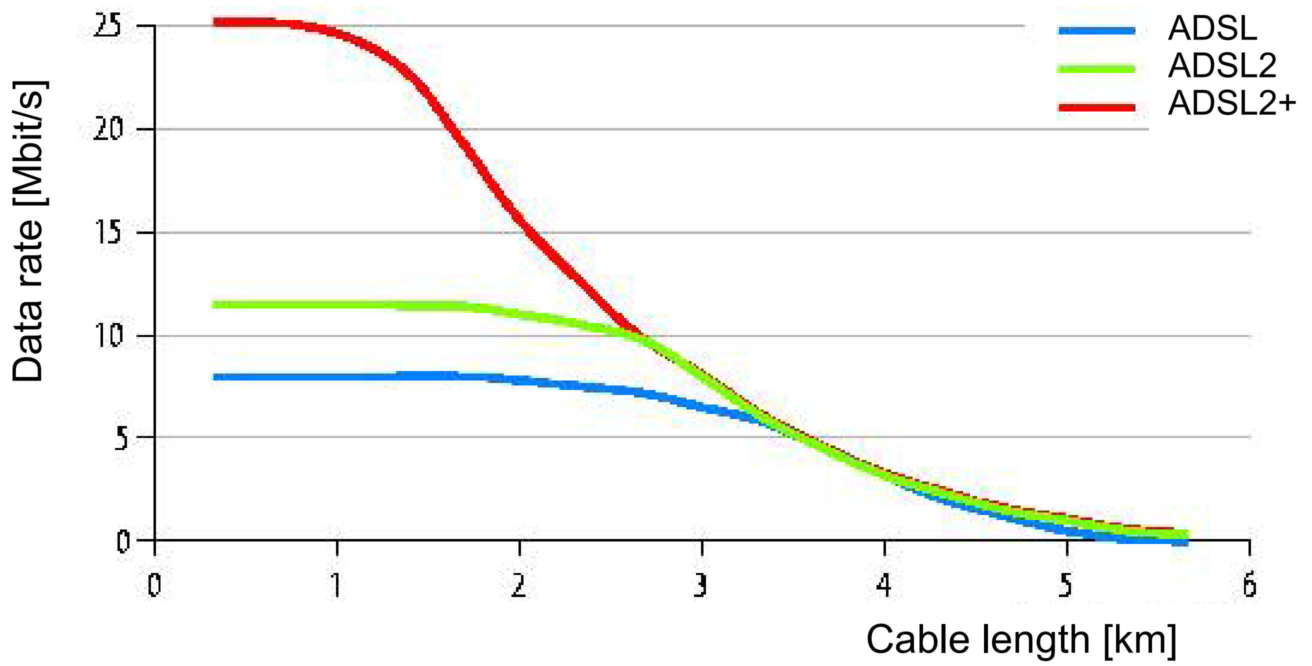


6.2.3 ADSL2, VDSL2

ADSL2

- Uses more frequencies (up to 2 MHz)
- Better encoding and signal processing
  - Less crosstalk
- Power preservation
  - Shutdown the modem when idle
- Adapting data rate *while* transmitting possible
- Downstream rate up to 12 Mbit/s possible (ADSL2+: up to 25 Mbit/s)
  - Upstream rate slightly increased to 1 Mbit/s

Comparison of Different Types of ADSL

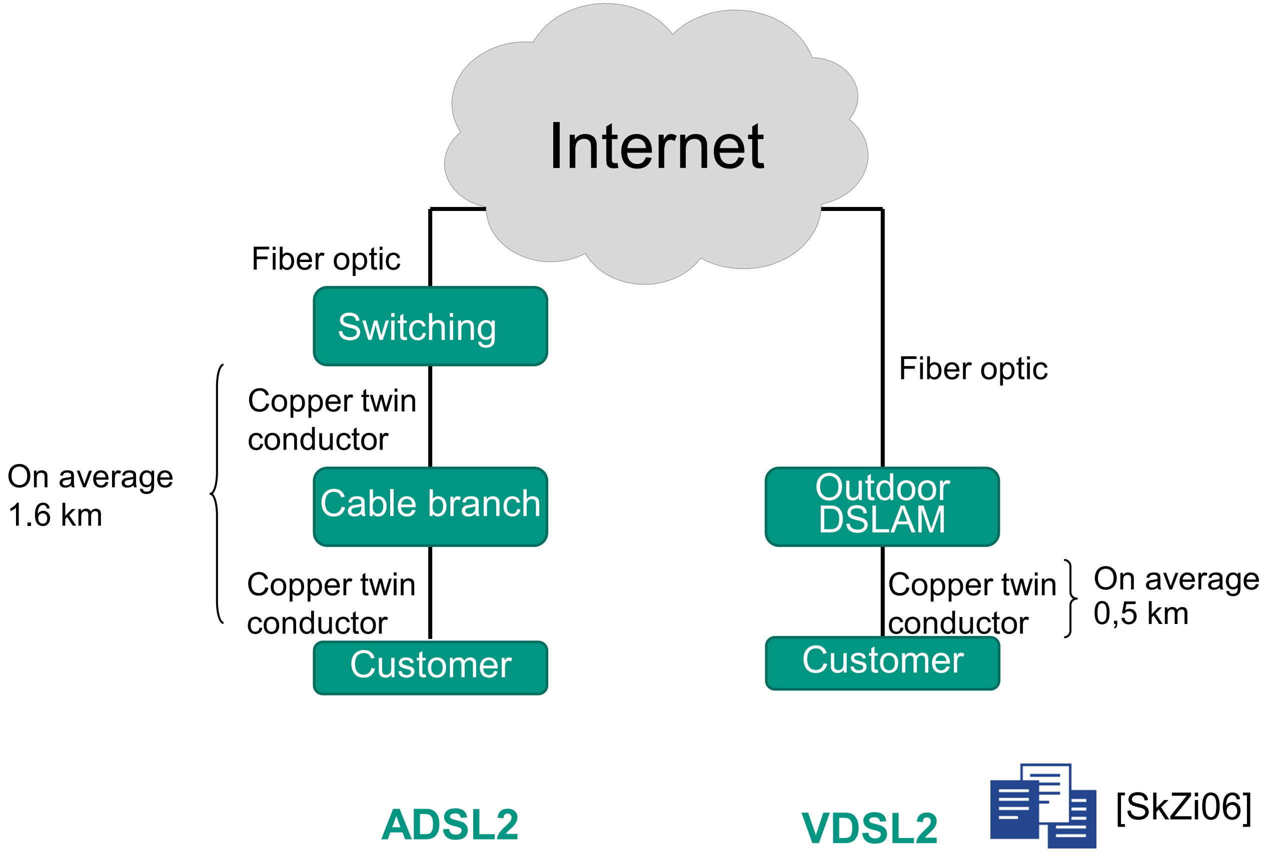


- ADSL2+ and ADSL2 are equivalent with distances longer than ~2.5 km
- All are equivalent with distances longer ~3.5 km

[Koss06]

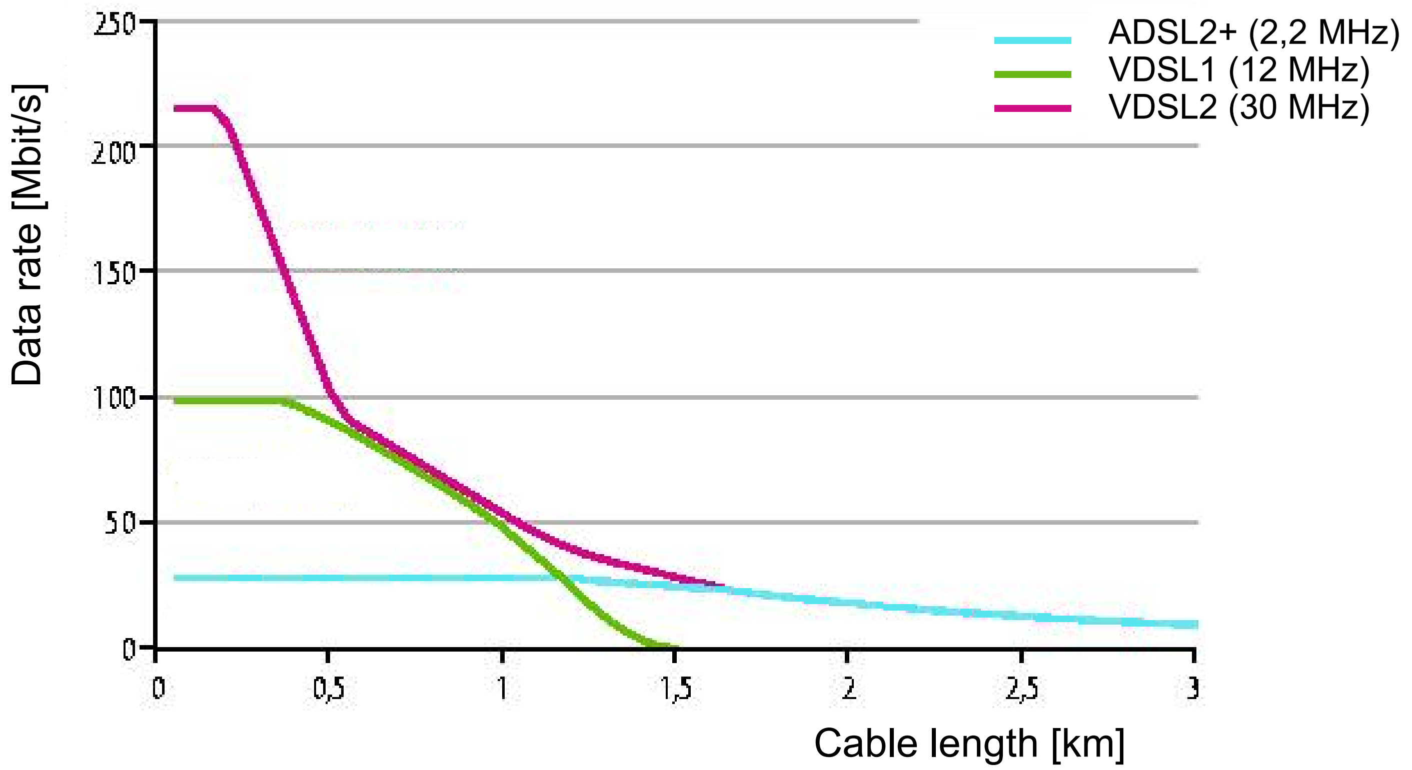
VDSL2

- Outdoor DSLAM
  - Placed closer to customer → shorter copper cable … higher data rate
- Uses more frequencies (up to 30 MHz)
  - In theory allows symmetric data rates up to 200 Mbit/s
- Only makes sense for very short distances
  - With higher distances no advantage compared to ADSL



[SkZi06]

Comparison of Different Types of ADSL/VDSL



- VDSL2 and VDSL1 are on a par with distances longer than ~0.7 km
- VDSL2 and ADSL2+ are on a par with distances longer than ~1.7 km

[SkZi06]

6.3 Cable Network

Cable TV Network

- Build up in the 80s

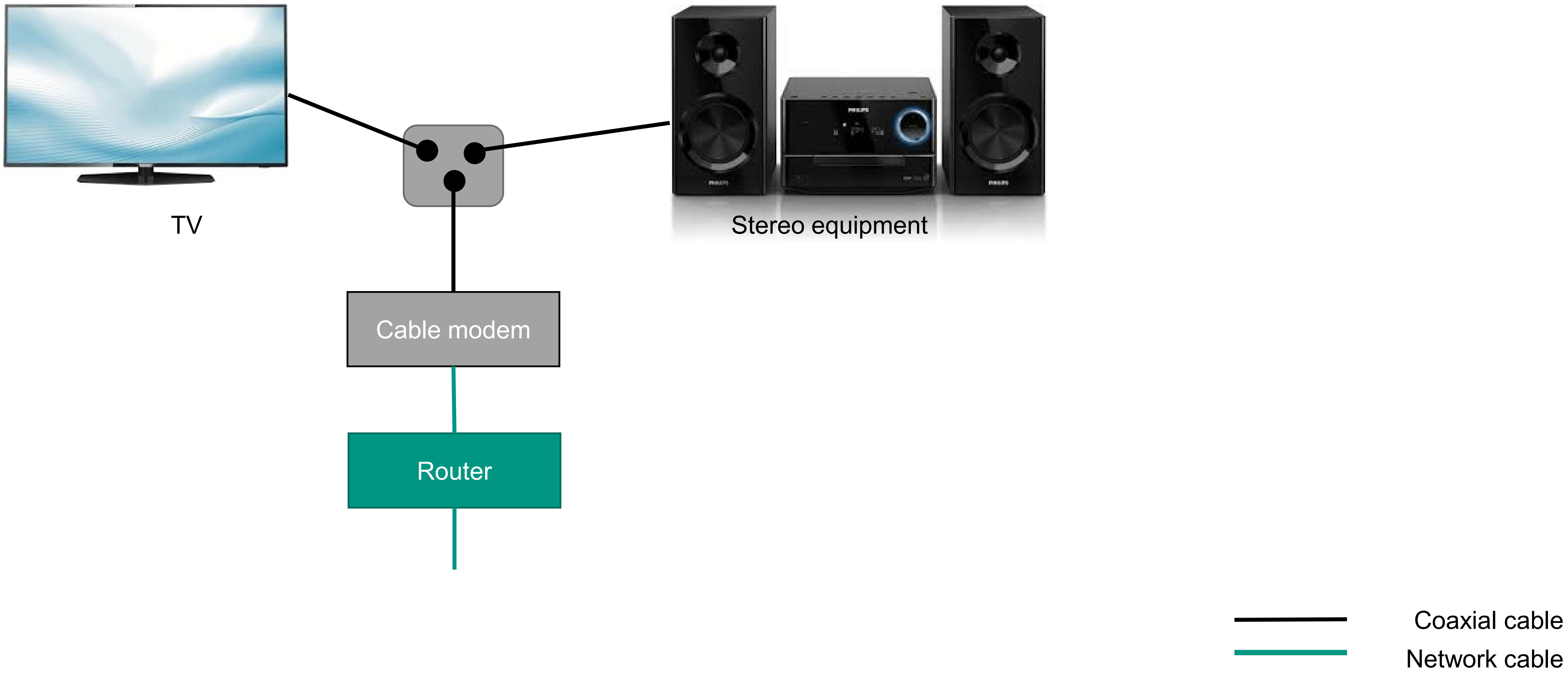
- Initially only designed for TV and broadcast transmission
  - Unidirectional to subscriber
  - No backward channel available

- Today also useable for telephony and Internet
  - Requires support of interactions (bidirectional data transmission)
  - Backward channel was integrated

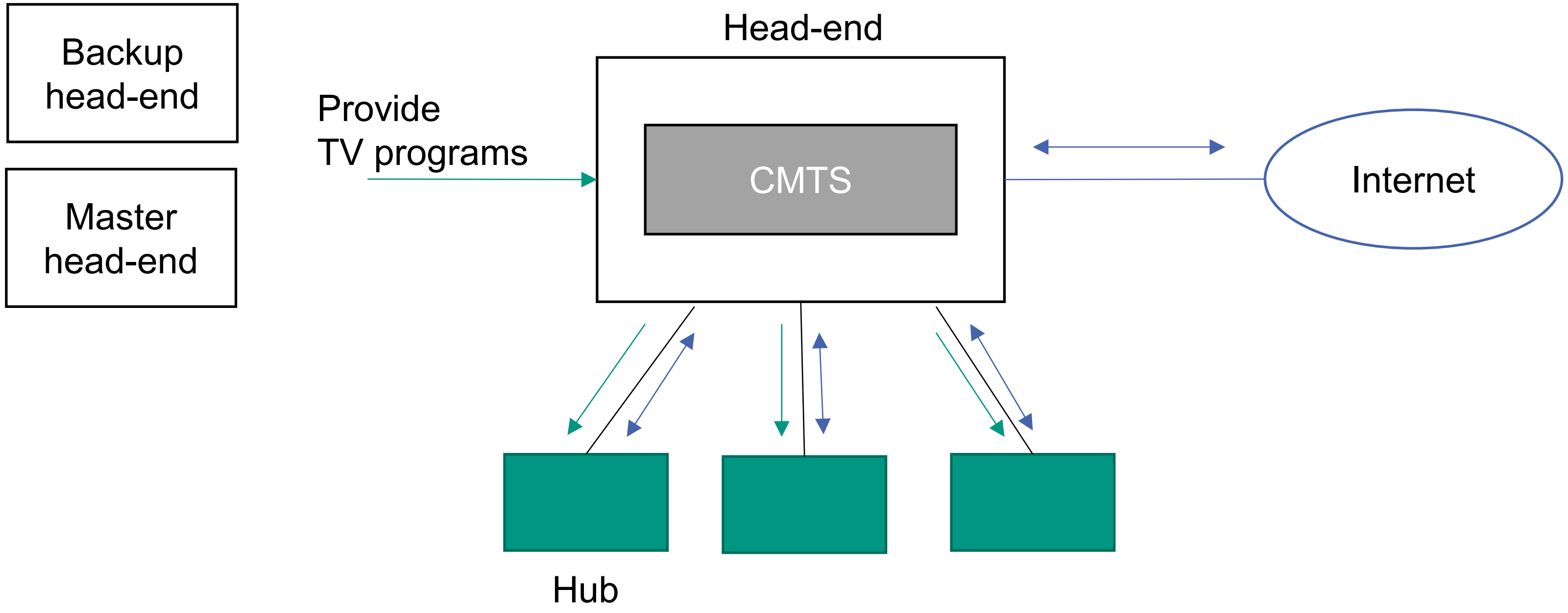
- Topology
  - Initially pure tree topology with coaxial cables
  - Today combination of fiber optic and coaxial cables
    - Tree topology only partially - close to the customer ("last mile")

- Availability
  - Cables reach around three quarters of all households in Germany

Configuration at Household



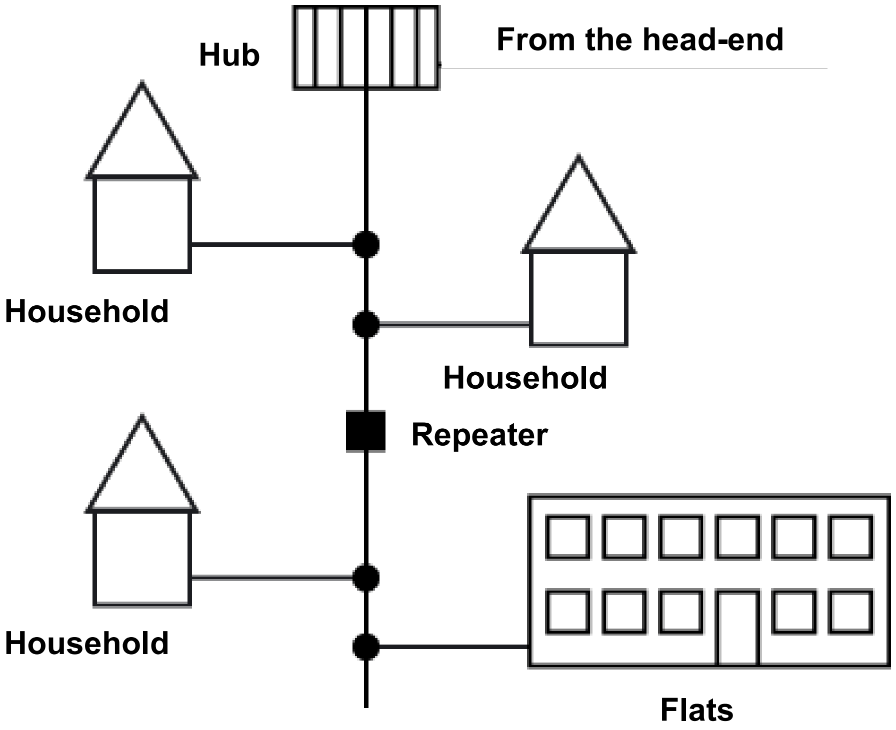
Architecture



- Switching system in cable network
  - CMTS: Cable Modem Termination System
    - Services up to 50000 customers

Architecture

- From hub to households

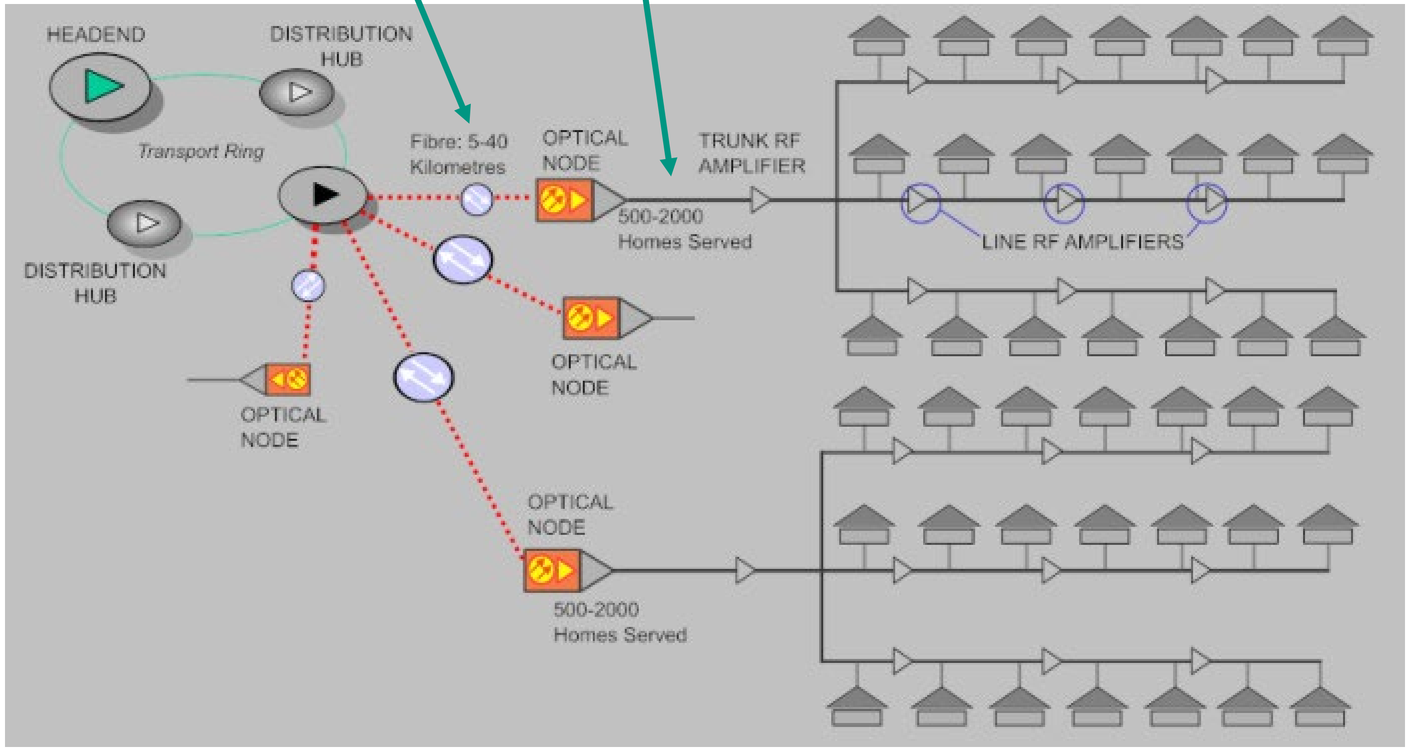


Tree topology,
coaxial cable,
shared medium,
around 5000 customers

[ElKo18]

Architecture

- HFC network
  - Hybrid fiber coax



Last mile (DOCSIS used)

Some providers seem to currently reduce number of customers per hub to about 500
→ network segmentation

Data Transfer

- Downstream
  - Broadcast: all subscribers receive same signal
  - Cable modem filters out “own” packets

- Upstream
  - Access to channels controlled by time multiplex (time slots)
  - Time slots are assigned by CMTS in the head-end

- Shared medium
  - Reachable data rate depends on number of concurrent users

Data Rate

- (Currently) useable frequencies: 5 MHz – 862 MHz
  - In practice often restricted to 570 MHz

  - Upstream 5 – 65 MHz (5 – 20 MHz often avoided due to interferences)
  - Downstream 500 – 600 MHz

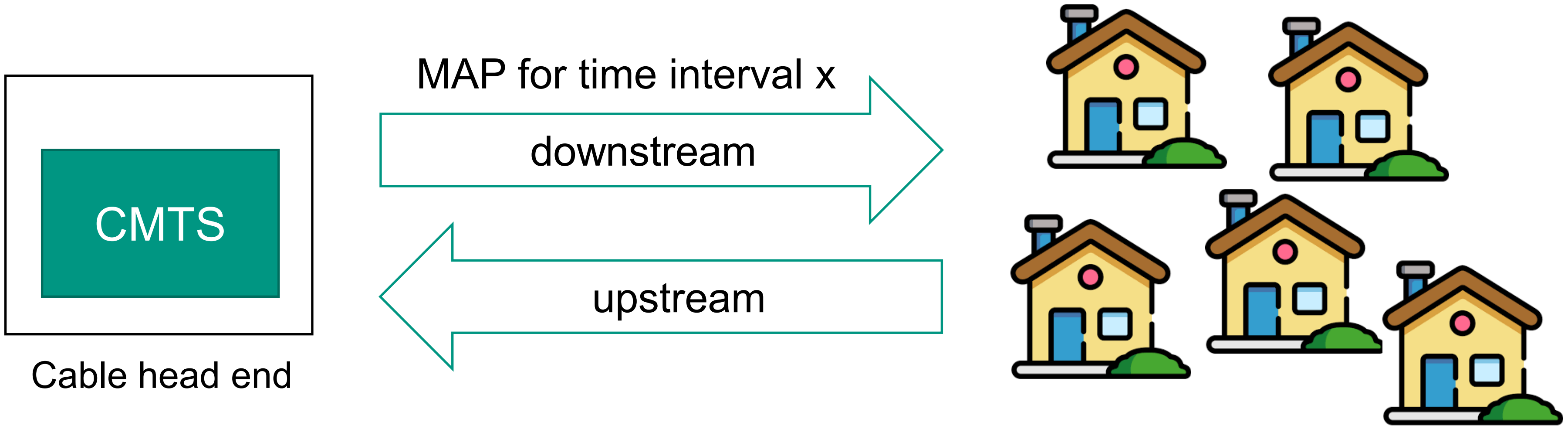
  - 100 channels à 8 MHz (in theory)
    - With QAM-256 50 Mbit/s per channel → in total 5 Gbit/s
    - For Internet traffic only 1 Gbit/s per head-end

- Data rate
  - Variable, shared, depending on specific installation situation
  - Downstream: up to 1 Gbit/s per customer
  - Upstream: mostly less

Standardization

- DOCSIS: Data Over Cable Service Interface Specification
  - DOCSIS 3.1
    - Permits usage of frequencies up to 1.7 GHz
      - But cannot be used (due to existing infrastructure)
      - With higher frequencies higher damping
      - In Germany upgrades only up to 1218 Hz
    - Uses OFDM
    - Data rates
      - Downstream: up to 10 Gbit/s
      - Upstream: up to 1 Gbit/s
  - DOCSIS 4.0
    - Standardized, but mostly not applied in Germany and Europe
    - Full duplex as well as Frequency Division Duplex
    - Data rates (still asymmetric)
      - Downstream: up to 10 Gbit/s
      - Upstream: up to 6 Gbit/s

DOCSIS: upstream / downstream



- Upstream
  - Multiple cable modems share same upstream channel (frequency)
    - → collisions can occur, MAC protocol needed
  - Time intervals with mini slots
    - request frames in mini slots reserved for that purpose
    - → collisions possible, exponential backoff
    - data frames in mini slots assigned from CMTS (through MAP message)
    - → no collisions in mini slots for data frames

Homework

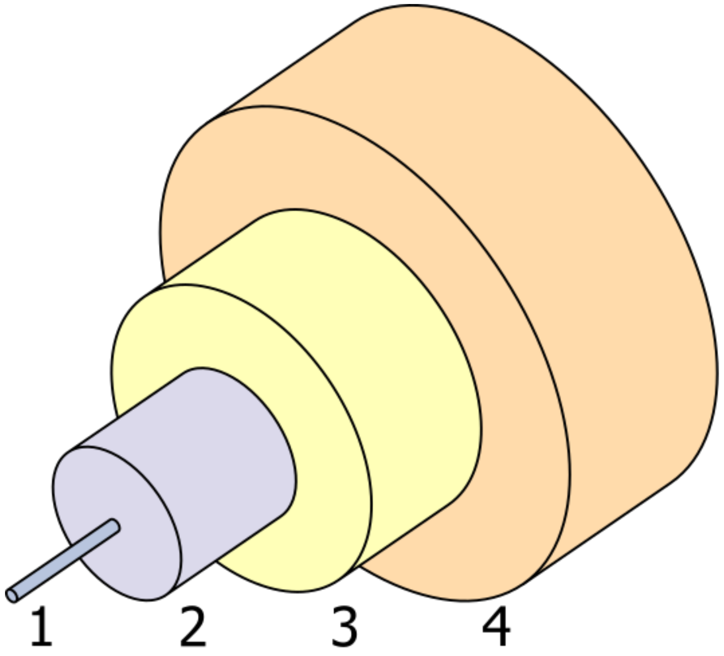
Homework 06-02

Access networks

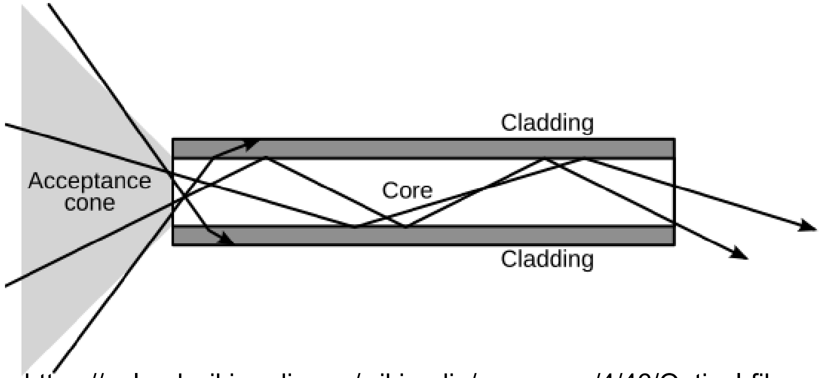
6.4 Fiber Optic

Optical Fiber

- Core (1)
  - Mostly highly pure silica glass
- Cladding (2)
  - Lower refractive index than core
  - Confines signal to core
- Buffer coating (3) & jacket (4)
  - Protective function
- Example: Multimode step-index fiber
  - In total <1 mm in diameter
    - Core 50 µm
    - Cladding 125 µm
    - Buffer 250 µm
    - Jacket 900 µm



https://upload.wikimedia.org/wikipedia/commons/8/84/Singlemode_fibre_structure.svg

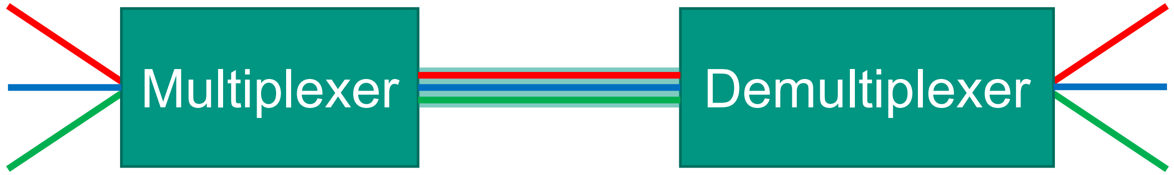


https://upload.wikimedia.org/wikipedia/commons/4/46/Optical-fibre.svg

[Keis21]

Transmitter & Receiver

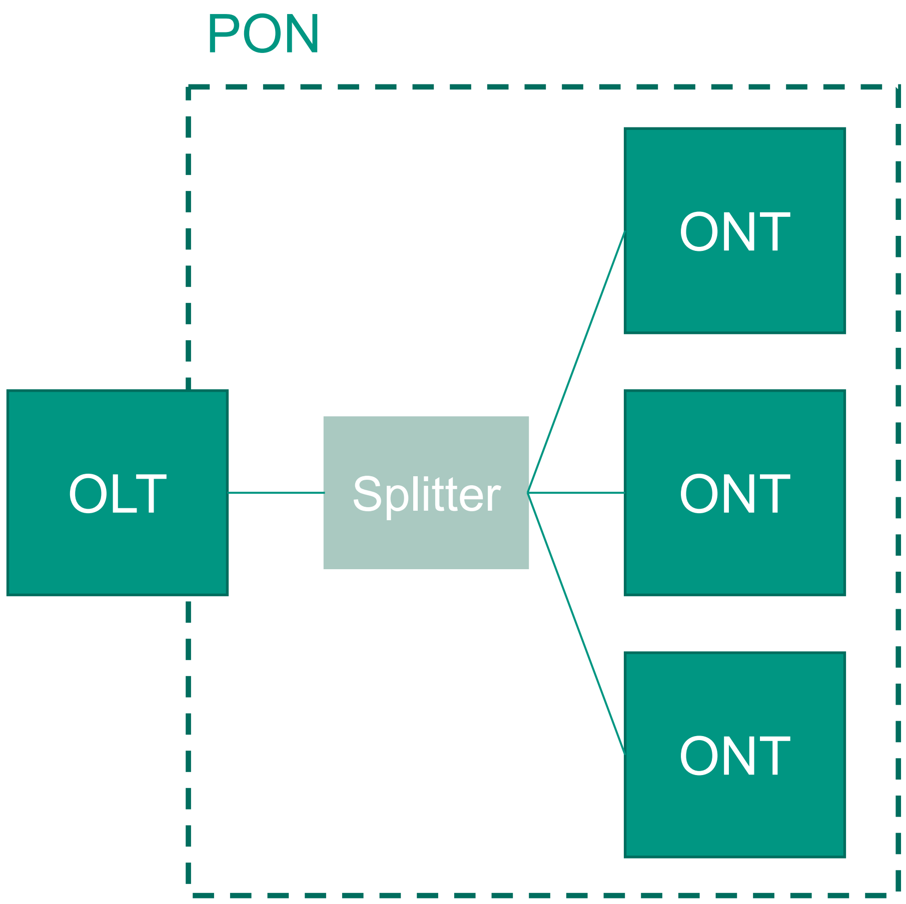
- Transmitter
  - Light sources
    - Laser diode
    - LED
- Receiver
  - Photodetector
- Wavelength division multiplexing (WDM)
  - Use different wavelengths on the same fiber
  - Coarse WDM
    - ITU-T G.694-2: 1271 nm to 1611 nm
  - Dense WDM
    - ITU-T G.694-1 specifies frequencies/wavelengths
    - Spaced around 193.10 THz (1552.52 nm)
    - 100, 50, 25 or 12.5 GHz channels
- Optical add/drop multiplexer (OADM)
  - Add or remove specific wavelengths to/from fiber



[Keis21]

Passive Optical Networks (PON)

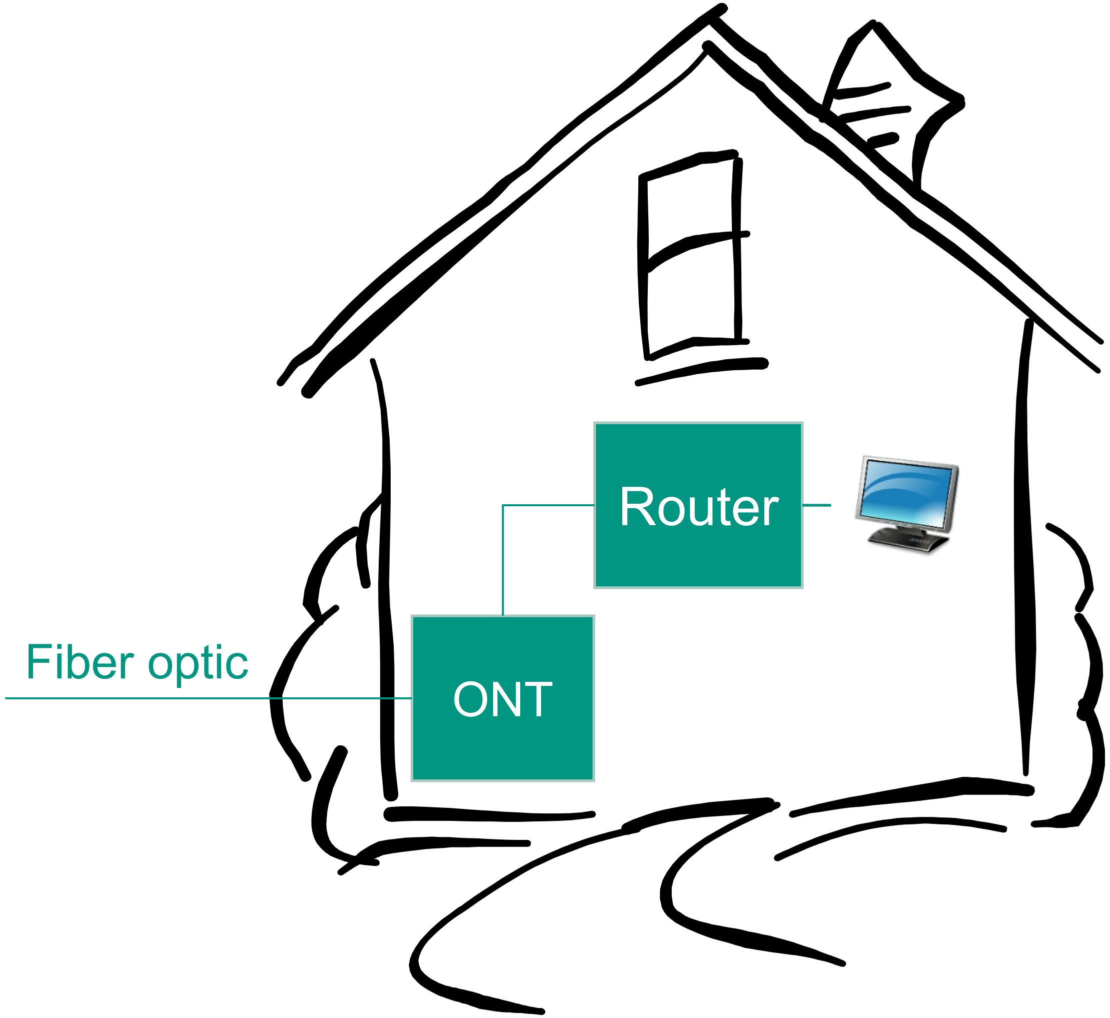
- Optical line termination (OLT) at provider side
  - Can control more than one PON
  - Coordinates traffic from/to ONTs
    - Downstream: broadcast
    - Upstream: time slots
- Optical network termination (ONT)
  - On customer premises
  - Terminates line and demultiplexes signal
  - Called optical network unit (ONU) if housed outdoor
    - But terms mostly interchangeable
- Splitter between OLT & OLT



[Keis21]

Fiber Optic

- Fiber optic ends at building or apartment
  - ONT can be combined with router
  - ONT also called “fiber modem”



FTTx … Comparison of Different Approaches

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- FTTx is a generic term (Fiber-to-the-…)
  - Encompasses different fiber optic configurations
- Fiber-to-the-Curb
  - E.g. DSL
  - ONU in DSLAM
- Fiber-to-the-Node
  - E.g. cable network
  - ONU in optical node
- Fiber-to-the-Home/Building
  - Often just called “Fiber optic”
  - ONT inside the building (FTTB) or apartment (FTTH)

FTTx … Shared Medium

- Fiber-to-the-Curb / DSL
  - Fiber optic shared until DSLAM
  - Then individual copper twin conductors
- Fiber-to-the-Node / Hybrid Fiber Coax
  - Fiber optic shared until optical node
  - Then coaxial cable used
    - Still shared medium
- Fiber-to-the-Home/Building
  - Fiber optic shared until splitter
  - Then individual fiber optics per ONT

6.5 Satellite Networks

Orbites of Satellites

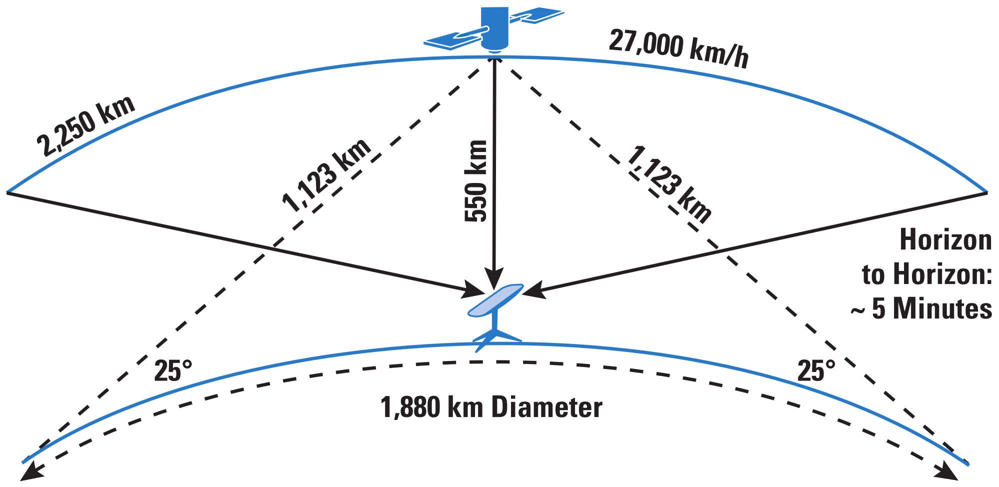
- Geostationary (GEO) satellites: 35786 km altitude above equator
  - User: satellite dish that points to a specific location in the sky
  - Satellites have size „of a large bus" and last for 15-20 years
  - Typical round trip time of 660 ms
- Medium Earth Orbit (MEO): altitude between 2000 and 36000 km
  - Example: Global Positioning System (GPS) (~20200 km, 21 satellites)
- Low Earth Orbit (LEO):
  - Altitude between 160 km and 2000 km
  - Smaller distance → smaller latency
    - Round trip times in the range of 10 - 50 ms
  - Less energy required to reach orbit compared to MEO & GEO

Focus on LEO satellites

[YoHu23]

Leo Satellites

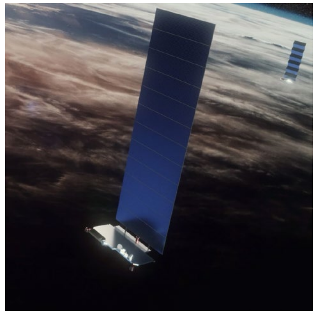
- Cover a limited area
  - 550 km height, 25° angle required
  - Circle with radius 940 km covered by 1 satellite
- Only visible for a short duration
  - Move at a speed of 27.000 km/h
  - Visible for ~5 minutes
  - Frequent changes of reachable satellite



[YoHu23]

Satellite System Components

- Satellites in orbit
  - Typically arranged in different orbital „shells“
    - Starlink: e.g., 550 – 570 km and 525 – 535 km
  - Examples: Starlink, Project Kuiper, OneWeb



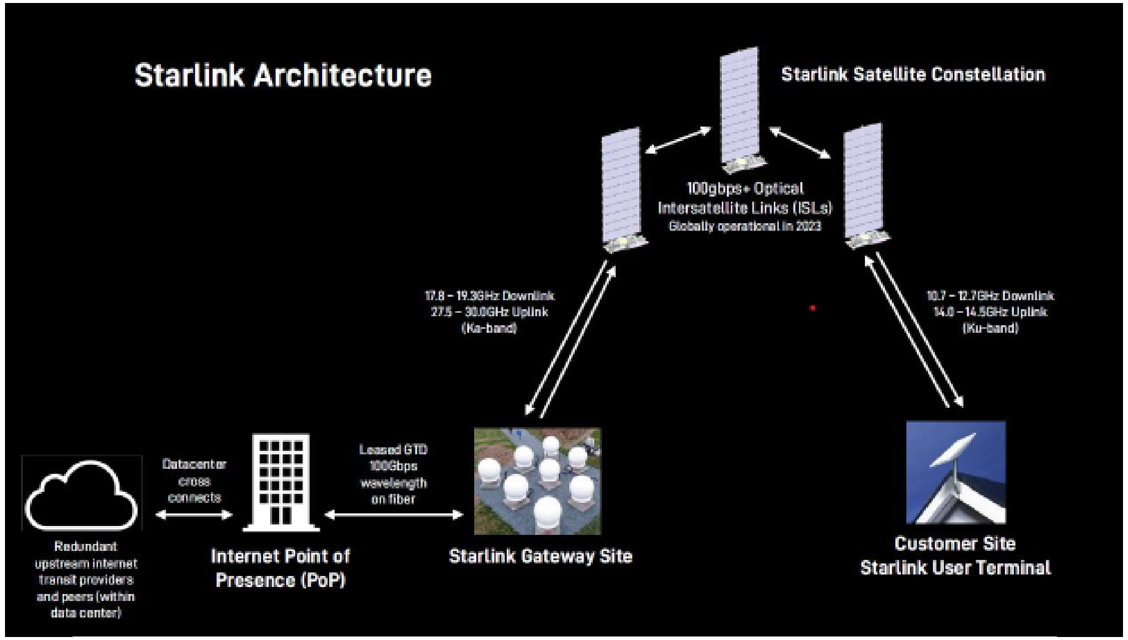
- User Terminal
  - Antenna
    - Phased array antenna
    - Parabolic dish antenna
      - Requires mechanical steering
  - Satellite modem

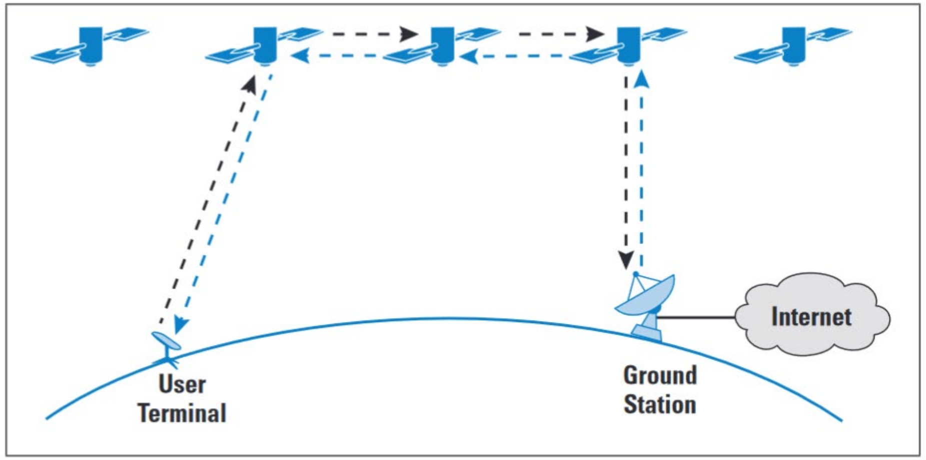
- Ground Station
  - Large antennas
  - Connection to the rest of the Internet

[Inne21, Star24]

Satellite Communication

- „mirror in the sky“
  - Satellites receive signal
  - Send signal to ground station
  - Use Ku (12-18 GHz) & Ka (27-40 GHz) band
- Communication between satellites
  - E.g. if no ground station in sight
  - Inter-satellite links (ISLs)
    - Laser communication
    - 100 Gbit/s
    - “SpaceX has dedicated considerable resources to developing [..] optical inter-satellite links (“ISLs”), and this information is highly proprietary”





[Arce22, InSo22, Wilt17, YoHu23]

Example: Starlink

- 7148 satellites launched
  - 6494 are in orbit
  - Altitudes between 525 km and 570 km
  - Each Falcon 9 rocket carries 40 – 50 satellites
  - Launch cost: below 2.000 $ per kg
  - Weight: 260 kg (v1), 295 kg (v1,5), 800 kg (v2 mini)

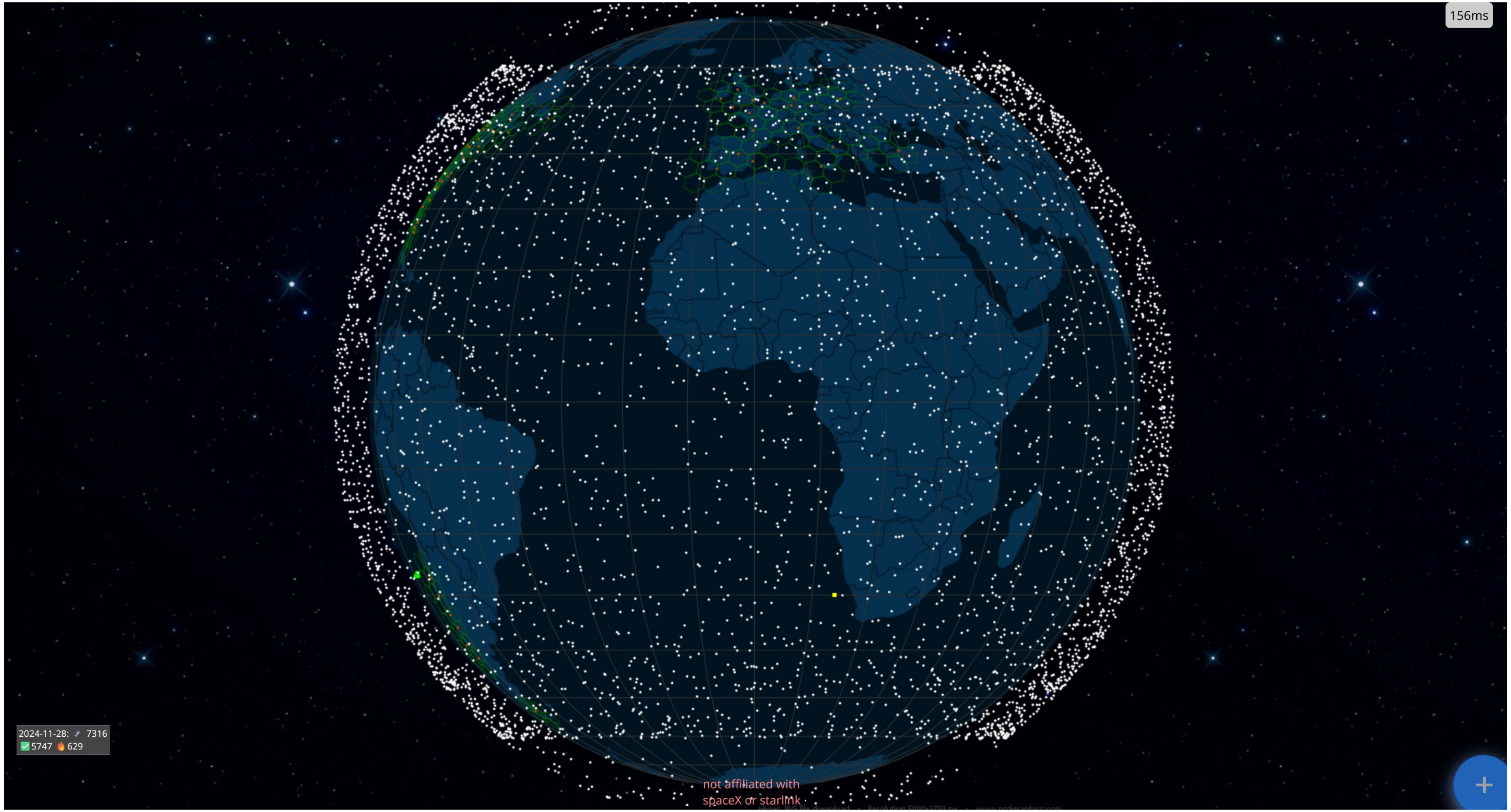
- Data rate
  - 40–220 Mbit/s download
  - 8–25 Mbit/s upload
  - Depends on current usage
  - 20–60 ms latency

- 50€/Month (private) up to 4713€/Month (business, maritime)

[McDo24, Star24]

Starlink

- Map of Starlink satellites



https://satellitemap.space/

Satellite Decomissioning

- LEO Satellites typically last around 5 years
  - Fuel spent after 5 years
  - Or have to be decommissioned because of regulations

- Two options
  - Graveyard orbit
    - 300 km above GEO orbit
      - Usually used for GEO satellites
      - Too costly (in terms of fuel) for LEO satellites
  - Deorbit
    - Satellite burns upon reentry into the atmosphere

[ESA05, FCC22]

Many Open Questions regarding LEOs

- Spectrum allocation and regulation
  - LEO spectrum coordinated by ITU-R but needs approval of nation
  - Orbital planes regulated on national basis
- Security and privacy
- Standards
  - Communication between user terminal, satellites and ground stations proprietary
- Environmental aspects
  - Decommissioning of satellites
  - Space debris
- …

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PROBLEMS

1) What is meant by full duplex operation in the context of Ethernet?
2) Do Ethernet standards with data rates higher than 1 Gbit/s implement CSMA/CD? Why?
3) The Rapid Spanning Tree Protocol operates at which layer?
4) What functions are performed by a bridge?
5) How is the root bridge determined?
6) How does a port state change to the forwarding state after a link failure?
7) How do the associated port roles change in case of a link failure?
8) What are important components of a DSL installation?
9) How is the available bandwidth used for telephony, upstream and downstream?
10) What is the typical topology of the cable network?
11) Using a cable internet connection, what are possible reasons for a worse internet connection on national holidays?