REAL-TIME NETWORKS
Ethernet

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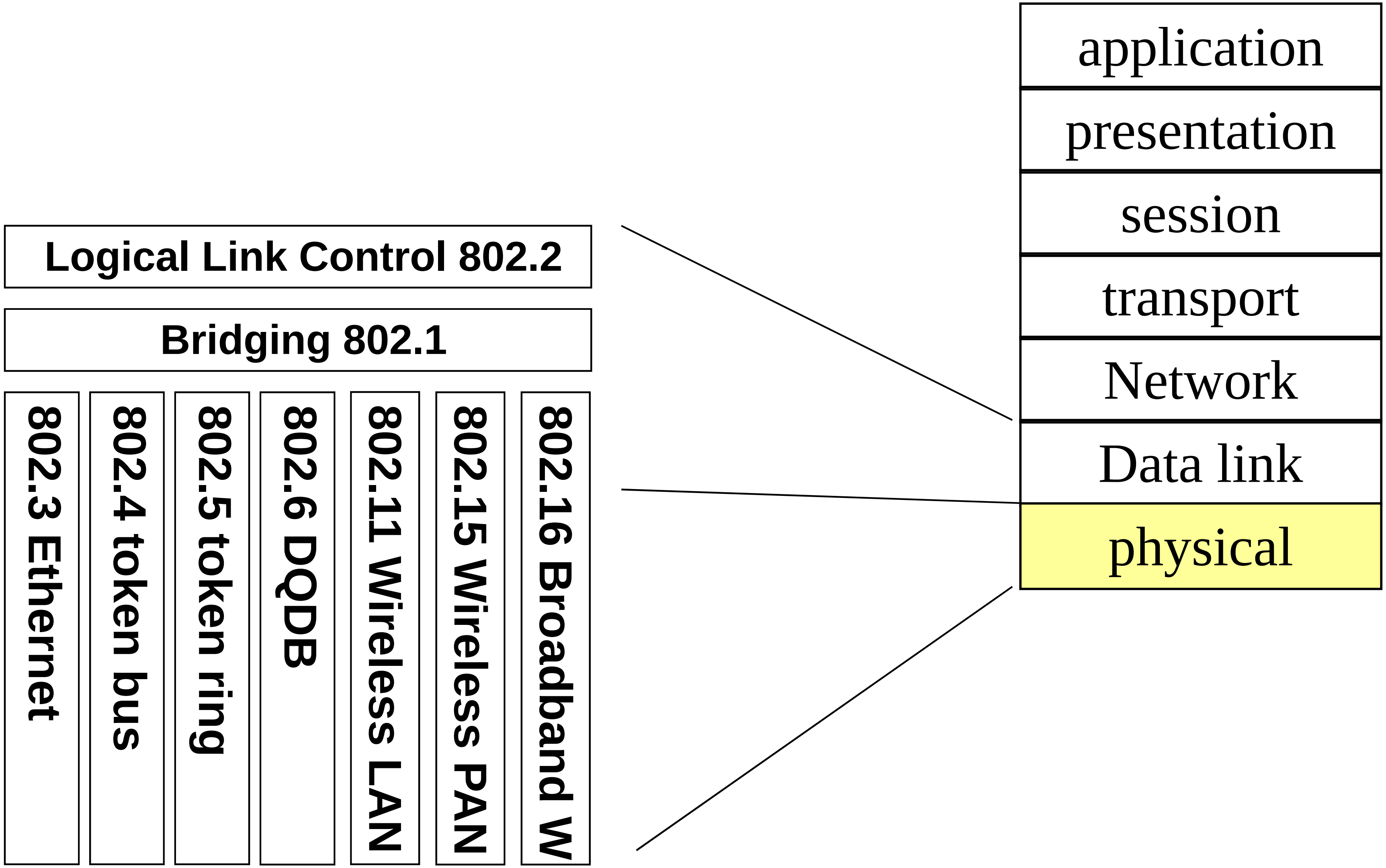
Outline

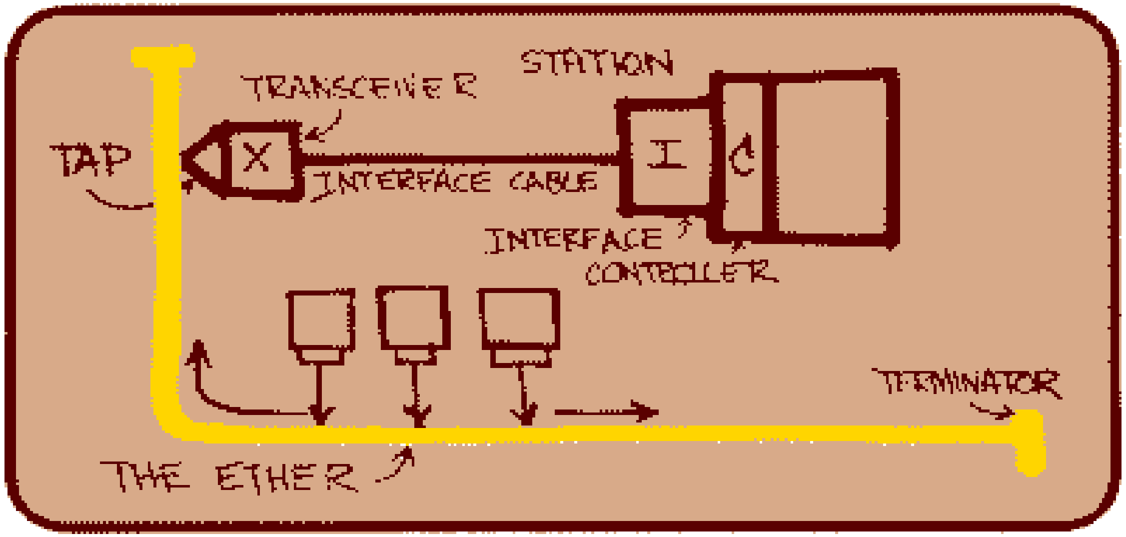
- The good old Ethernet
- Myths and realities
- Companion protocols
- Improvements
- Switched Ethernet
- How to improve temporal behaviour
- Industrial Ethernet
- Experiments on Switched Ethernet
- Conclusion

IEEE 802 standards



« Vintage Ethernet »

- One segment of coaxial cable
- All nodes are hooked to the same cable
- A medium access control
  - Every station may listen what is emitted on the bus (cable segment)
  - Each station may listen to what it emits
- Packet transmission



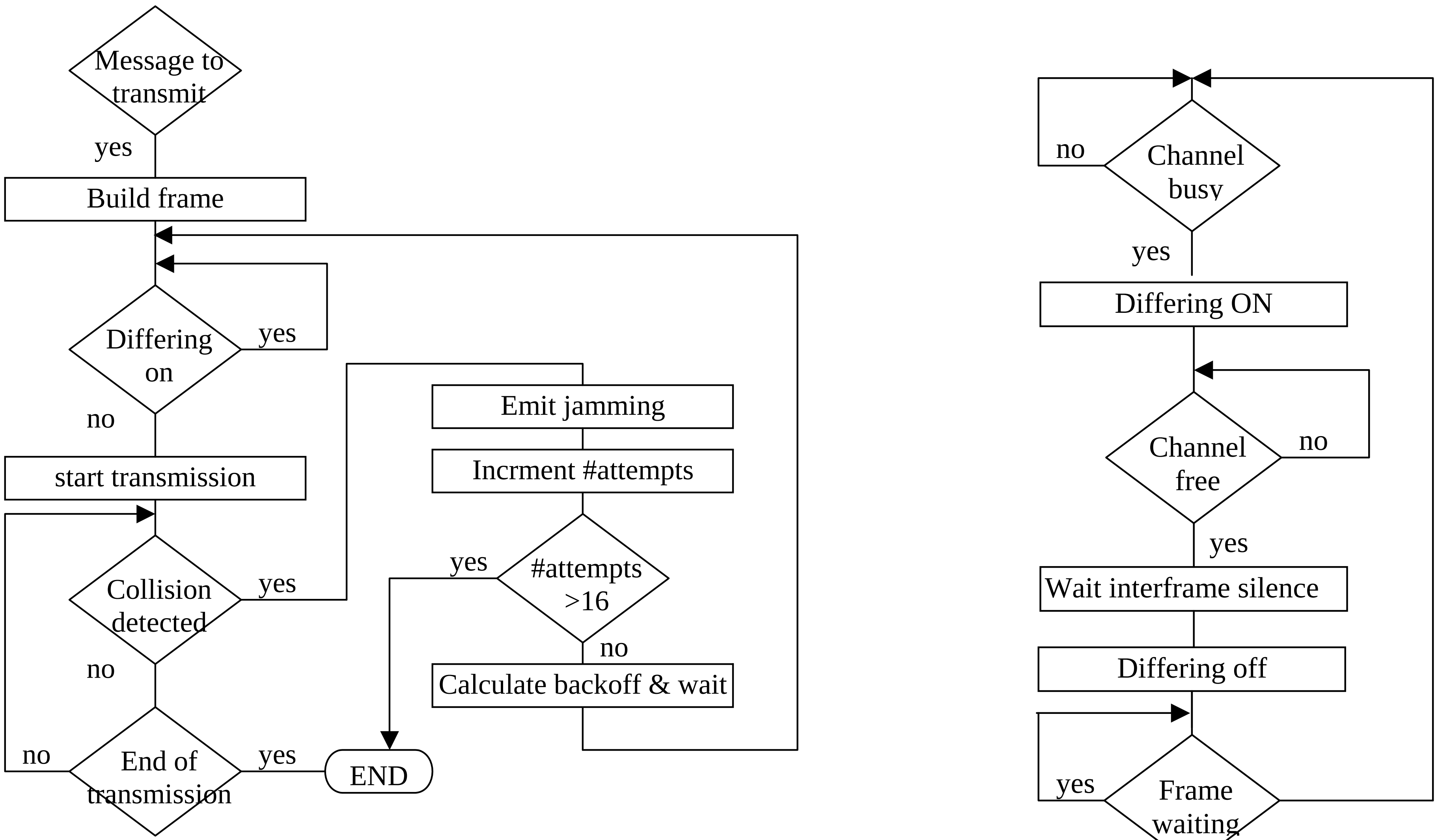
Basic principles - emission

- A station that wants to transmit
  - Listen the transmission medium
  - If free during a given duration
    - Emits its message
    - While listening what is sensed on the cable
    - If there is a collision, it sends a jamming sequence et prepares to retry
  - If the medium is busy, the station waits until it becomes free and does as indicated above
    - 1-persistent CSMA/CD

Basic principles – retry in case of collision

- Not done immediately
- A number is chosen randomly in the backoff interval
- This number is multiplied by the slot duration (5µs à 100Mbit/s)
- Starts to transmit after the given duration (if medium is busy)
- If there is a collision, the backoff window is doubled
  - Maximum of 0..1023
  - After 16 attempts, transmission is cancelled
- When transmission is successful, the backoff interval returns to its original value [0..1]

CSMA/CD for Ethernet

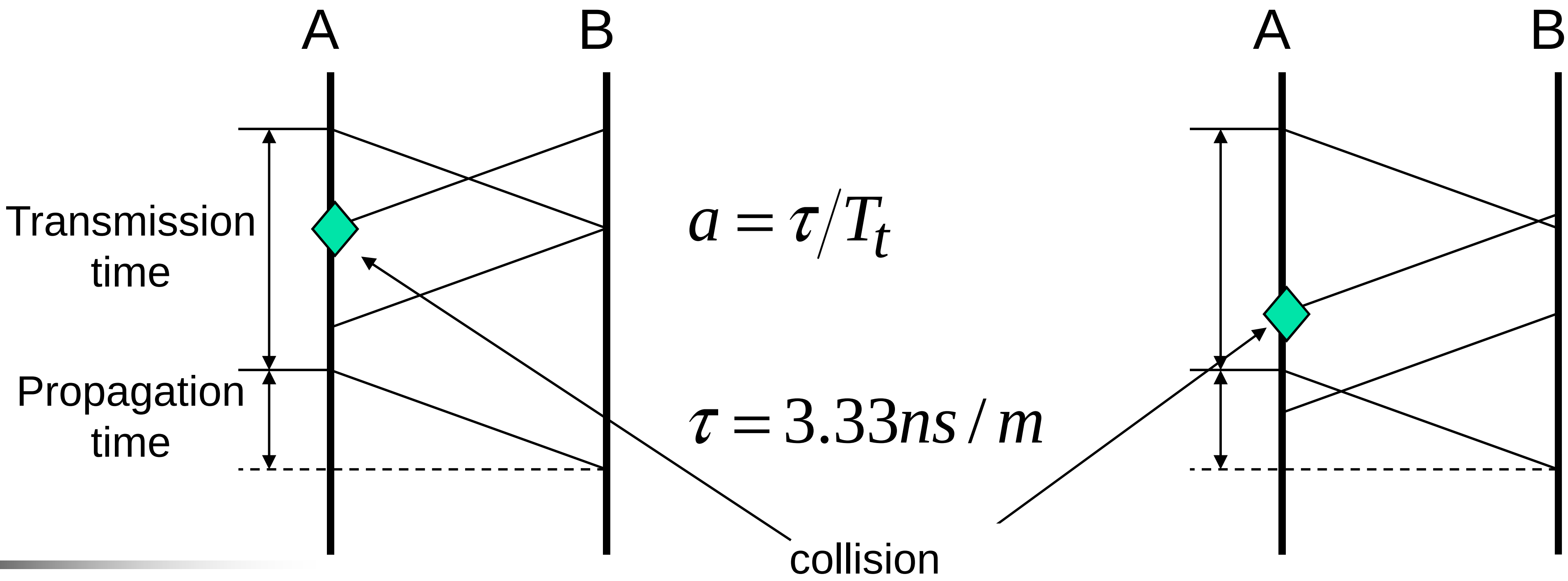


Backoff

- In case of collision
  - Transmission is stopped after sending the jamming sequence
  - the backoff interval is calculated
    - $[0..2^m-1]$ where m is the number of successive collisions
- A number is selected randomly in this interval
- Waiting time = selected number t . « slot time »
  - Slot time = 512 bit time (4096 @ 1Gbit/s)
- After each collision, the interval is doubled
  - Maximum interval of [0..1023] after 10 attempts
- In case of success, m is reset to 0

Collisions

- Collision zone = 2 x propagation time
  - This defines the « slot time »
  - Limits the cable length and defines the minimal size of a packet



$$a = \tau / T_t$$

$$\tau = 3.33 ns / m$$

Parameters (10base5)

- 50 ohms coaxial cable (thick ethernet)
- 10 Mbit/s
- Interframe silence = 96 bit time (9.6µs)
- « slot time » = 512 bits (51.2µs)
- Distance < 2500 m. between 2 stations
  - 5 segments of 500 m and 4 repeaters
- Minimum frame size = 512 bits
- Maximum frame size = 1518 octets
- Jamming sequence size = 32 to 48 bits

History

- 1970: ALOHAnet is developped at Hawai University
- 1976: Bob Metcalfe and David Boggs make a talk at the National Computer Conference
- 13 déc. 1977: U.S. Patent #4,063,220 - Multipoint data communication system with collision detection
- 1982: 1st version published by Xerox, Intel and DEC
- 1985: first 802.3 standard

Conventions

Speed	Transmission	Medium
1	BASE	-2
10	BROAD	-5
100		-36
1000		-T, -T2
10G		-F, -FB, -FL
		-X

Ethernet Frame

preamble	SFD	Destination address	Source address	Type / length	802.2 header and data	FCS	ESD
7 bytes	1 byte	6 bytes	6 bytes	2 bytes	46-1500 bytes	4 bytes	1 byte

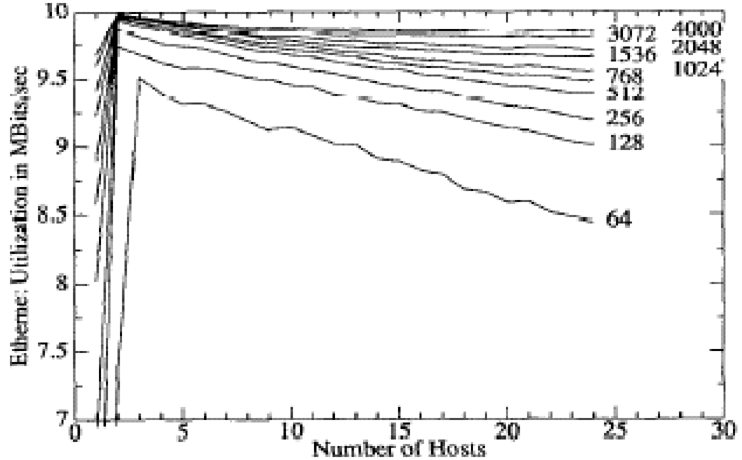
- MAC address
  - 24 bits: identification of manufacturer (Organization Unique Indentifier)
  - 24 bits: assigned by the manufacturer or the vendor

Vintage Ethernet Performances

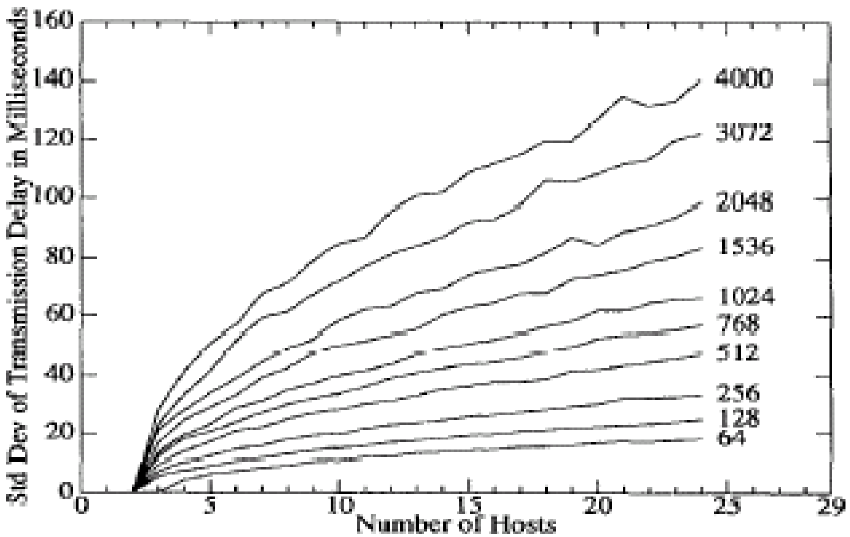
- Difficult to establish in theory
- A maximum throughput of 37% is often mentionned
  - This is only valid under simplified asumptions and small packets
- In practice
  - Access delay are minimal in case of low traffic
  - Transmission delay increases linearly with the size of the packets and the number of nodes
  - The delay standard deviation also increases but more slowly

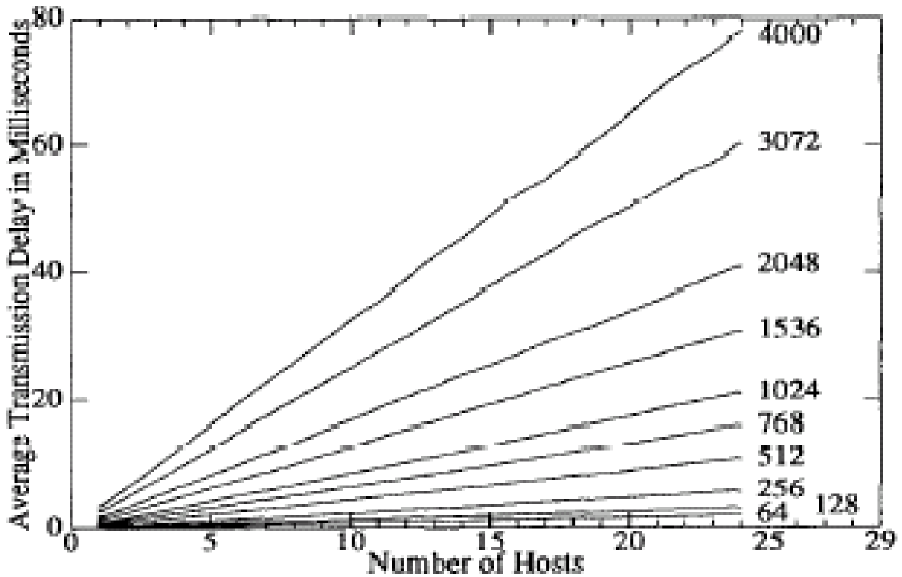
Measured performances at 10Mbit/s

- Mean delay
- Its standard deviation



Source Boggs, 1988





What makes a difference between theory and practice

- Calculations are complicated ⇒ simplified asumptions
  - Poisson arrival law
    - In practice, it is less smooth
  - Infinite population and always waiting packets
  - Packets are dropped due to buffer overflow
- In reality
  - Cable lengths are much smaller than the maximum allowed
  - Packet sizes according to a bimodal distribution
    - Lengths close to min and lengths close to max.

Problems

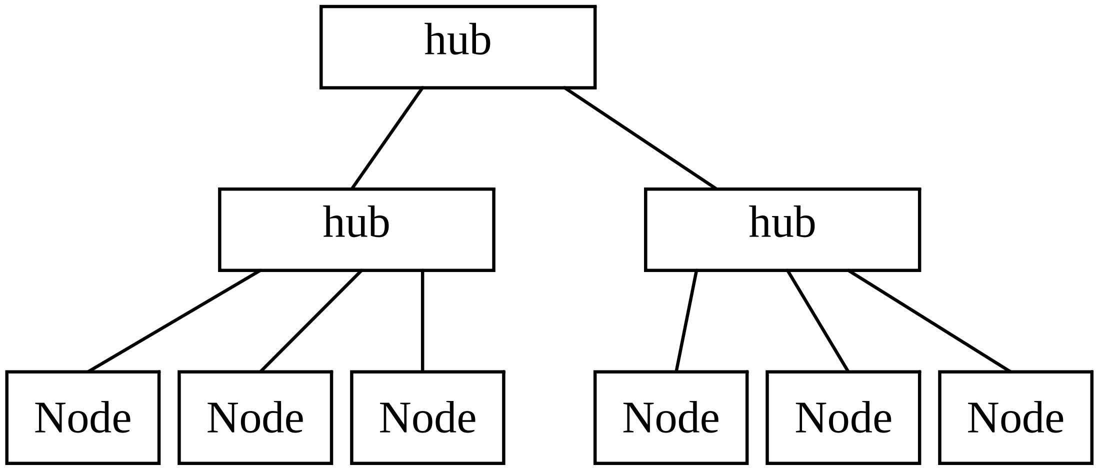
- « capture effect »
  - Assume 2 stations A and B have a lot of messages to send
  - At a given time, their emissions collide
  - A chooses 1 as a random number and B elects 0
  - Thus B succeeds at its first attempt
  - As B has more traffic, it attempts to send the next message right the way
  - This will collide with A second attempt
  - A has to double the backoff interval while B has the initial one
  - B has hence more chance to succeed than A, ….. And so on
- Unbounded transmission time
  - Not exact but !!!

Companion protocols

- IP: Internet Protocol RFC 791
- TCP: Transport Control Protocol, RFC 793
- ARP: Address Resolution Protocol, RFC 826
- IGMP: Internet Group Management Protocol
- ICMP: Internet Control Message Protocol,
- RARP: Reverse Address Resolution Protocol, RFC 903
- DHCP: Dynamic Host Configuration Protocol, RFC 2131-2
- IPv6, BGP, OSPF, RIP, NAT, …..

Improvements

- 1987: 1BASE5: 1Mbit/s on twisted pairs with hub
- 1990: 10 Mbit/s
- 1995: 100 Mbit/s
- 1998: 1 Gbit/s
- 10 Gbit/s
- 1997: full duplex
  - Hub replaced by a bridge (switch)



Parameters

- Distances on twisted pairs < 100m.
- Distances with optical fibers < 40 km (10G)

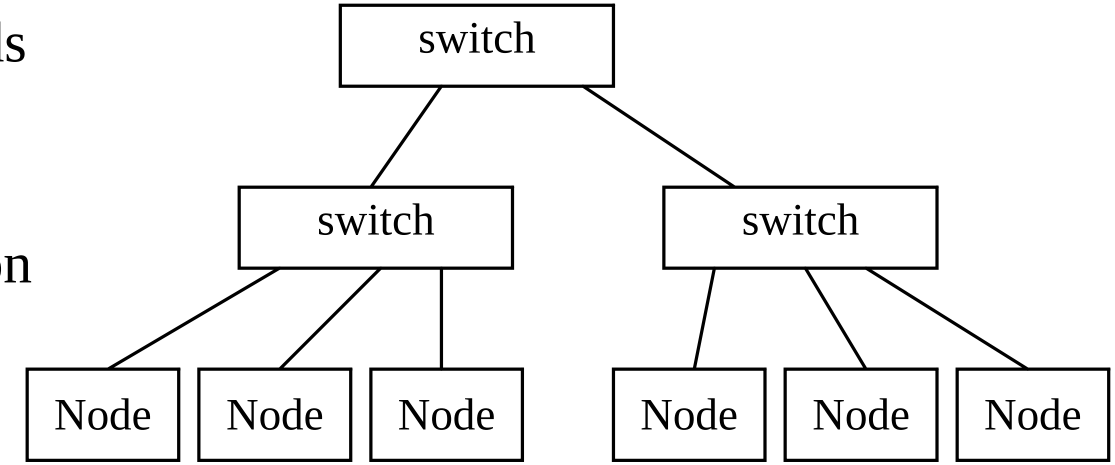
Speed	Interframe space	Slot time
10	96 bits	512 bits
100	96 bits	512 bits
1000	96 bits	4096 bits
10G	96 bits	NA

Switched Ethernet

- The original Ethernet operates in a half duplex mode
  - One station transmits or another but not both at the same time (except in case of collision)
- With a hub (repeater), there are only 2 nodes on a cable (hub + end node)
  - However the behavior must be the same as if all nodes share the same cable (collision domain)
  - This is necessary to detect possible collisions
- A switch
  - Receives on a port
  - Re-transmit on the port(s) toward the destination(s) of the packet
  - In between, it stores the packet

Switched Ethernet (2)

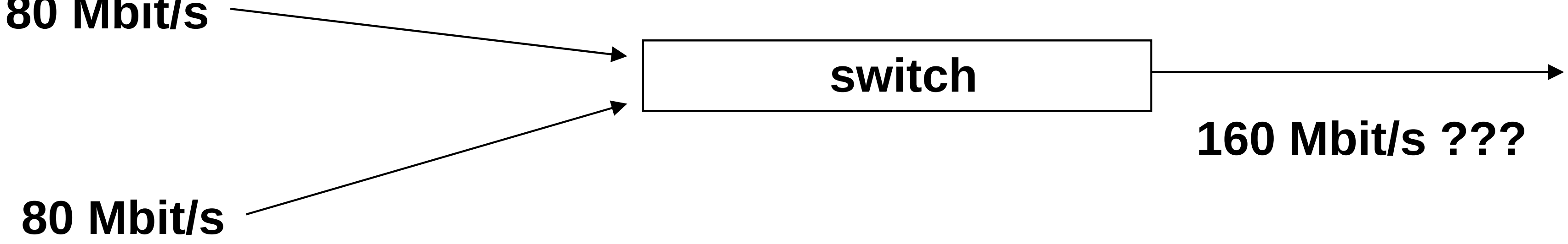
- With a switch, there are no longer collisions
  - An end node no longer needs to detect the collisions
  - As in a twisted pair cable, there a pair for each direction
    - Both directions may be exploited simultaneously



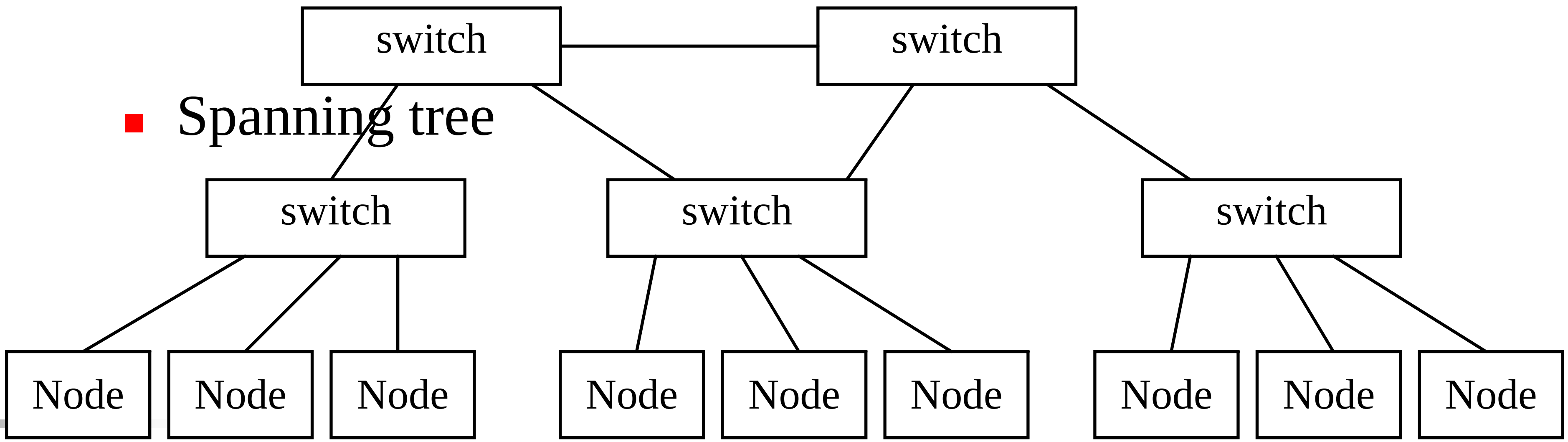
- Each link may hence be potentialy exploited at twice the speed
- The available bandwidth is potentialy higher (multiple domains)
- That does not mean that all problems are solved

Switched Ethernet (3)

- Switch buffers may overflow
  - If two nodes send traffic to a third one ⇒ PAUSE frame



- What about multiple paths between two nodes
  - Spanning tree

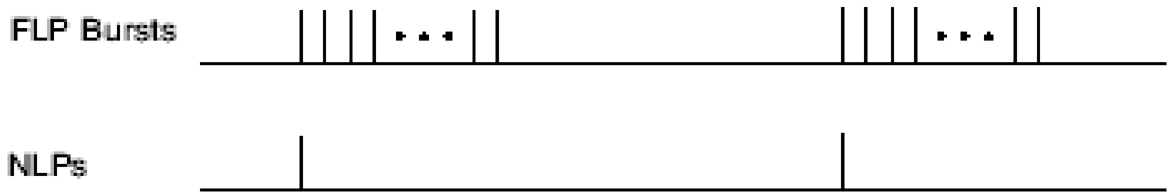


Hubs and switches

- Sometimes misleading
  - Hub 10/100 is a switch
- Multilayer switches
  - Include a routing module and a switching module

Complementaty aspects

- Auto negociation
  - every 16ms +/-8



- VLAN – IEEE 802.1Q
  - A way to isolate traffic among a group of nodes
  - Uses the « type/length » field
  - Add a LAN identifier (12 bits) and a priority field (3 bits)
- Quality of service – IEEE 802.1D (includes 802.1p)
- Self learning
  - Switches may learn on which ports the nodes are reachable
  - Multicast raises a problem
    - IGMP snooping

Quality of service management

- According 802.1D (MAC bridges)
  - Not only for Ethernet
  - 8 traffic priorities
    - Most switches only implement « best effort », « real-time » and « management » on each egress
    - Packets arriving in a ingress port are inserted in the queue corresponding to the priority at the egress port (FIFO order within a priority level)
    - When the output link is free, the oldest packet of the highest priority is transmitted
      - This may cause priority inversions which are quite long (1500 bytes)
    - Packets that have no priority field or those that enter through selected ports may be forced at a given priority level
      - Very useful to filter the traffic coming from outside
- !!! This is not to be confused with QoS at network level such as IntServ or DiffServ

How to improve QoS in Ethernet ?

- Access time
  - Modify the MAC
  - Add another MAC on top of CSMA/CD
    - Pure TDMA, master/slave, token, reservation, etc.
  - Adapt the traffic
  - Use of switches
- Synchronisation, dating, consistency
  - Clock synchronization algorithms

Add another MAC

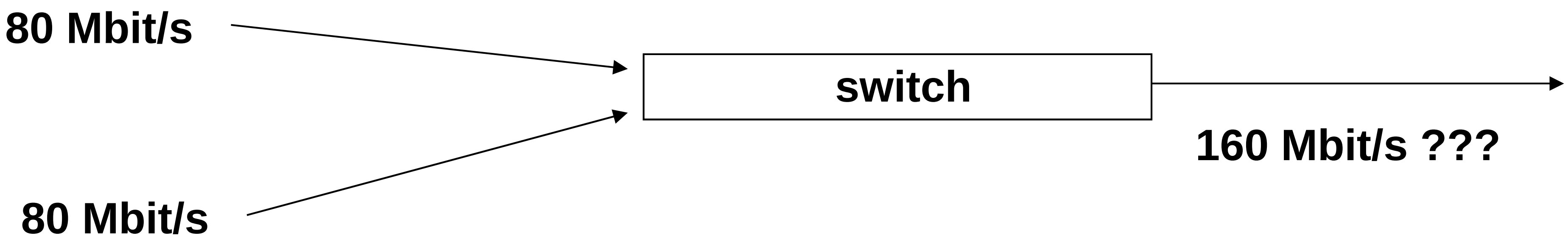
- A number of such proposals
- Nearly all MAC types have been suggested
- The MAC used in many fieldbussses has been used
- Generaly speaking, rather inefficient
  - Pure TDMA @ 1Gbit/s $\Rightarrow$ 4% utilization

Traffic adaptation

- Avoid bursts due to non real-time traffic
  - smoothing (limit traffic instantaneous intensity by delaying part of it)
  - shaping (periodic emissions by blocks)
- This only adds statistical guarantees
  - Reduces drop rate and jitter
  - Increases mean delay

Use of switches

- Avoids collisions
- Queues in switches may however overflow



- Increases mean delays and increases jitter

Clock synchronization

- Using messages to synchronize and provide simultaneous sampling is not possible (unless exception)
- Accuracy γ of synchronization depends on the uncertainty ε in the transmission delay
  - $\gamma \geq \varepsilon\,(1 - 1/n)$ where n is the number of participating nodes

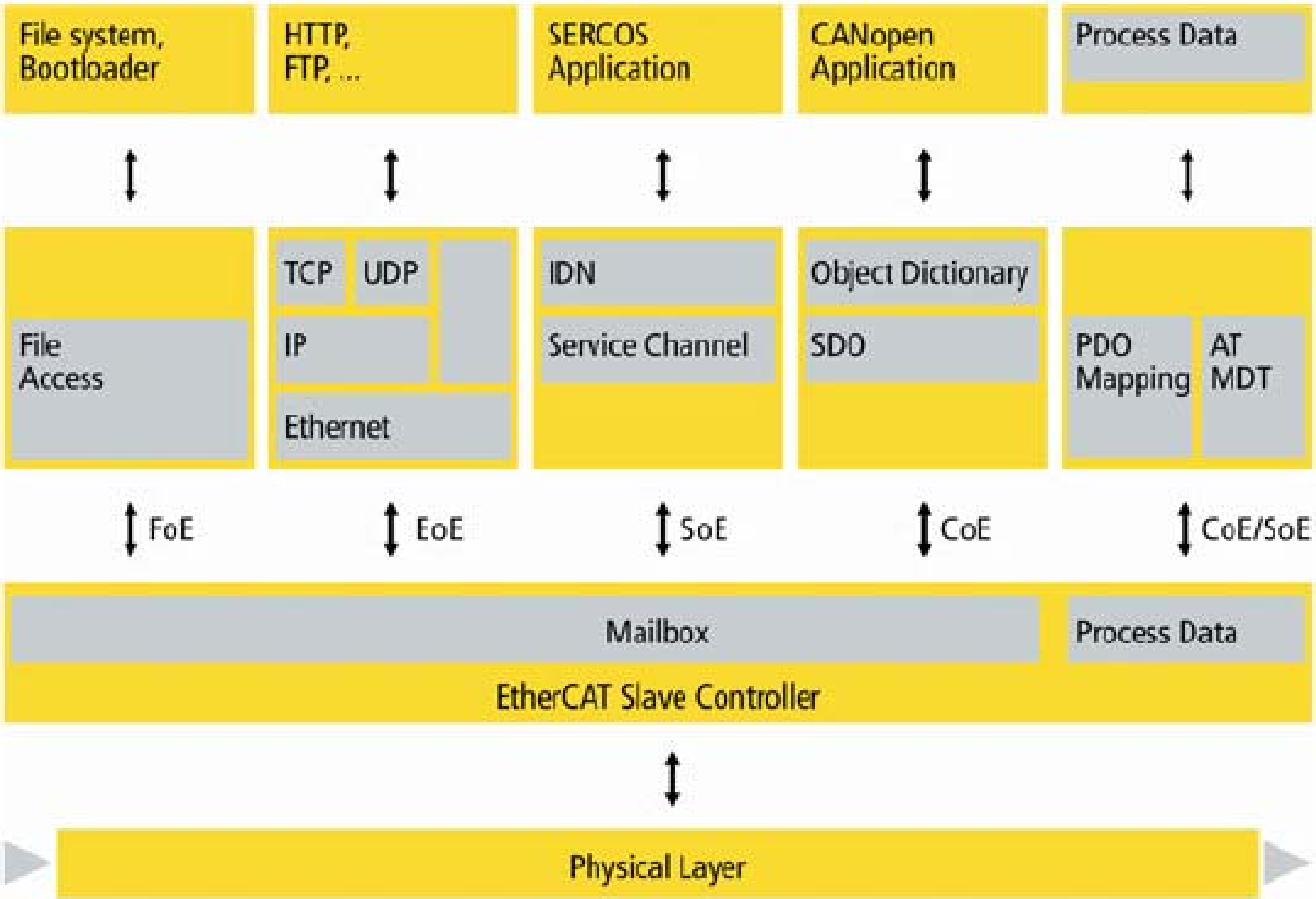
Current RT Ethernet contenders

- Non standard hardware
  - EtherCAT
  - SynqNet
  - SERCOS III
  - PowerDNA ?
- Standard hardware but not compatible with regular 802.3 nodes
  - Ethernet Powerlink
  - FTT-Ethernet
  - TTP over Ethernet (TTE)
- Standard hardware, compatible with regular 802.3 nodes
  - PROFINET
  - JetSync
  - EtherNet/IP (+CIP)
  - Modbus-TCP
  - Real-Time Publish-Subscribe
- And a number of academic proposals

EtherCat

- General topology with 65535 nodes / segment
  - Wide choice of cable from twisted pair to optical fibers
- Synchronisation based on distributed synchronized clocks
  - Claim accuracy to microseconds
- Quite performing
  - 100 axes in 100µs; 1000 I/O points in 30 µs
- Compliant with IEEE 802.3u Fast Ethernet
  - All protocols based on IP are supported (TCP, UDP,...)
  - Dedicated hardware (except for the master)
- Integration with CANopen and SERCOS profiles for compatibility with legacy
- Node to node communication only via master

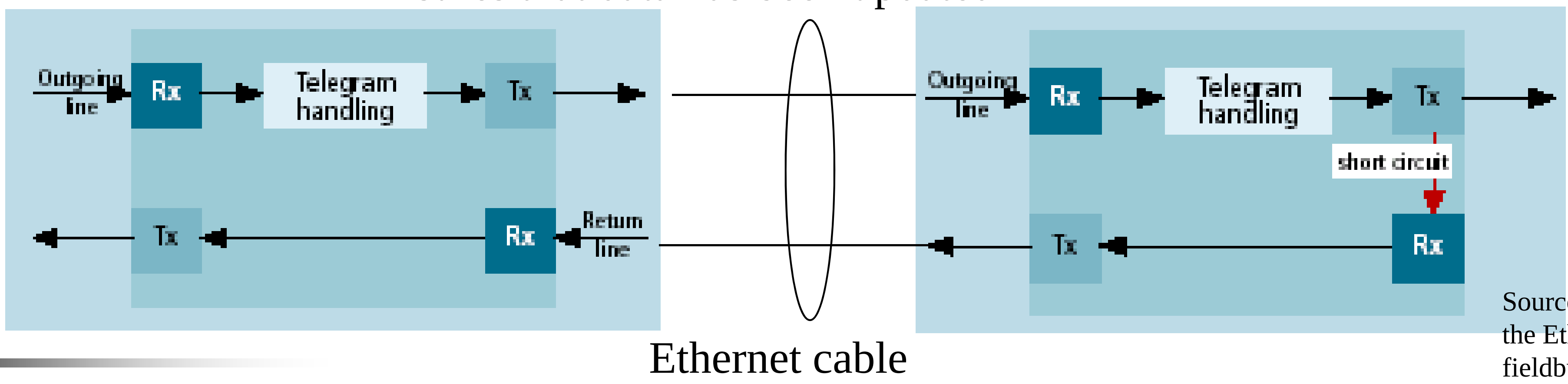
EtherCat – Architecture & protocols



EtherCat technical introduction and overview, dec. 2004

EtherCat – Principles

- Master sends an Ethernet frame
  - That contains one or more EtherCat datagrams
    - Contains data for the outputs and has room for the input data
    - Nodes read and update part of the frame on the fly
    - Location in datagram is independent from the physical localization
- Inside each slave, there is a sync manager
  - That informs of the reception of new data
  - That manages the data read and write order
    - Ensures that data has been updated



Source: EtherCat the Ethernet fieldbus,

EtherCat - analysis

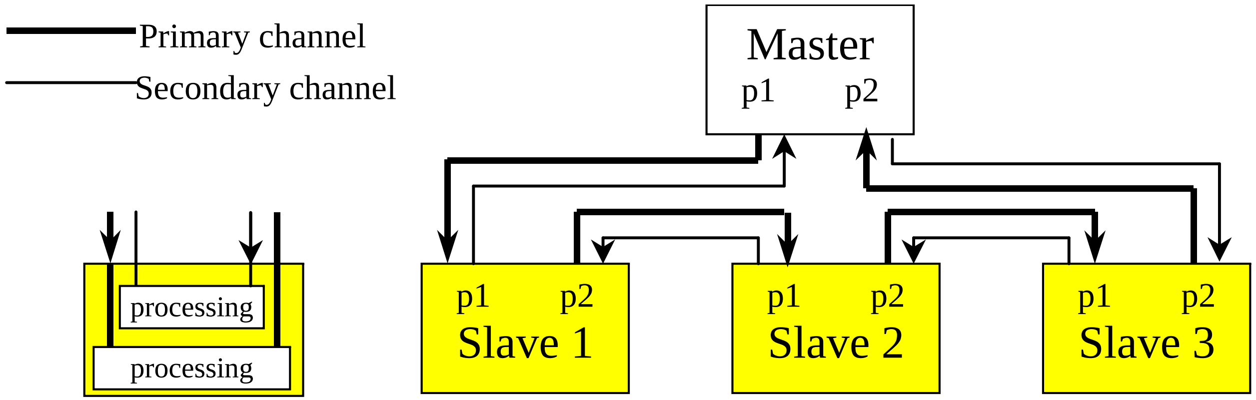
- Advantages
  - Very fast (is this useful ?)
  - Standard hardware for the master
  - Compatible with legacy CAN Open or SERCOS
- Drawbacks
  - Targeted to inputs and outputs which is not sufficent in many cases
  - Incompatible with Ethernet
  - Requires specialized hardware
  - Restrictive topology

SERCOS III

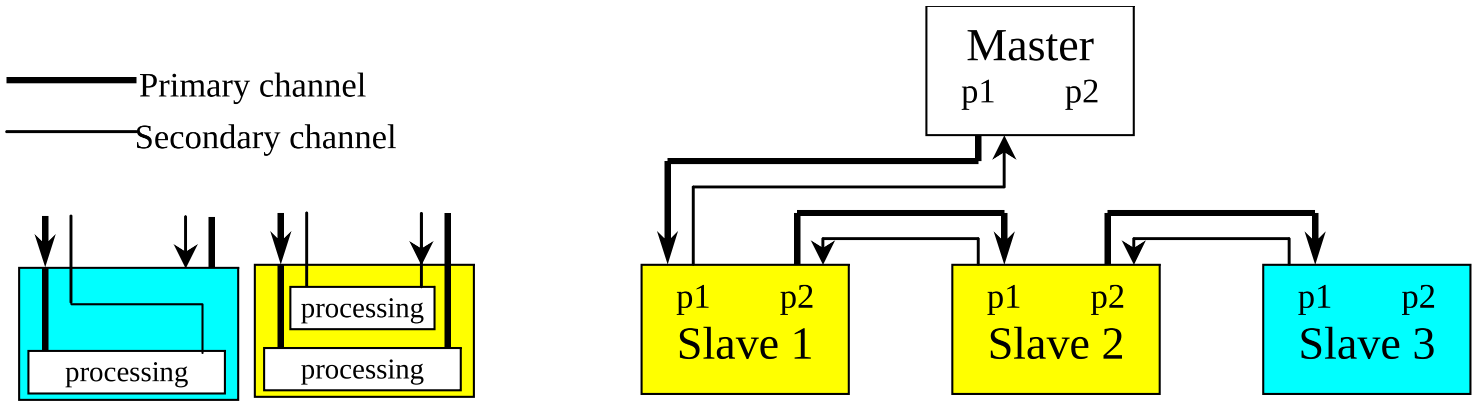
- Up to 254 nodes on a single segment
  - Line or ring topology
    - Medium redundancy capability
- So-called « guaranteed and deterministic communication »
  - Cycle time from 31.25µs (62.5, 125, 250 and n x 250µs)
  - jitter <1µs (or 50µs for the low performance class)
- Compliant with IEEE 802.3u Fast Ethernet (fiber and copper)
  - IP based protocols are supported (TCP, UDP,...)
  - Implementation on dedicated hardware
- Integration SERCOS profiles
- Possibility of real-time node to node communication

SERCOS III - Topology

- Ring



- Line

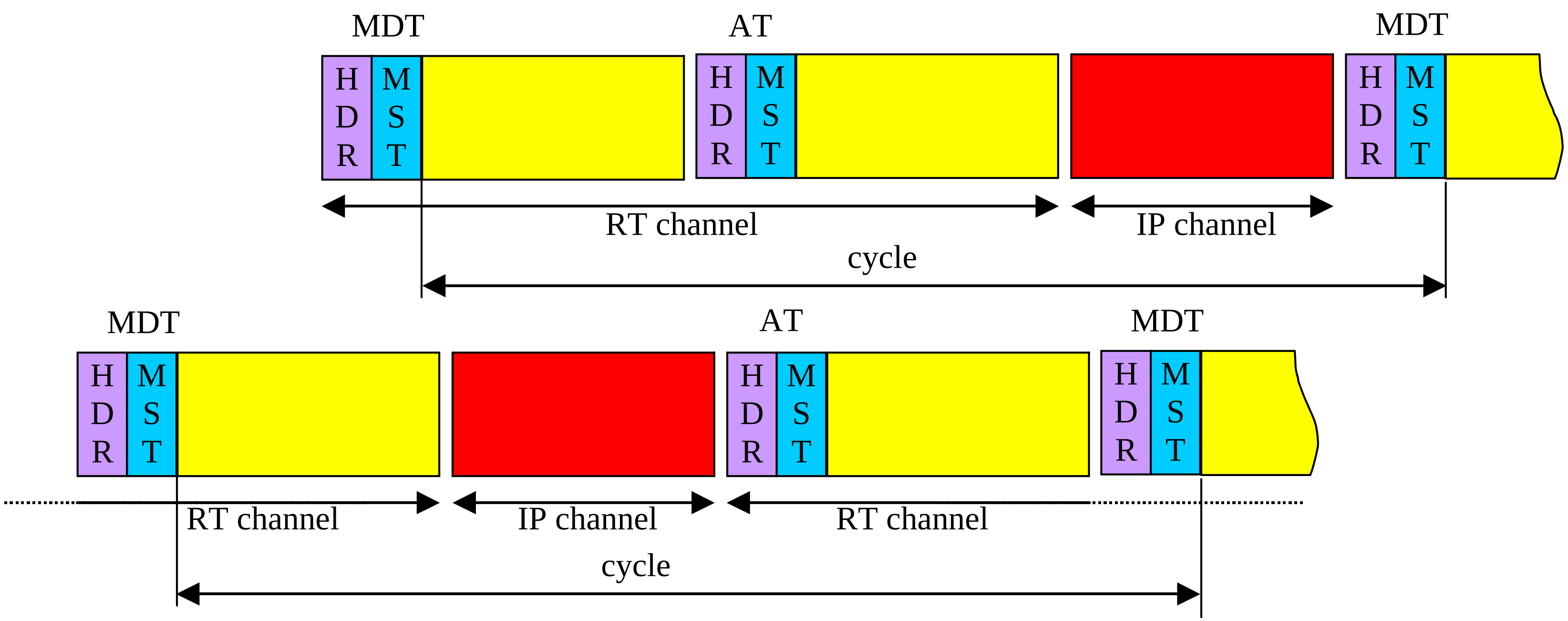


SERCOS - cycle

- Real-time channel present in each cycle to
  - Synchronize the slaves with the master
  - Exchange data and commands between the master and the slaves
    - In each cycle (real-time)
    - On request (service channel)
  - Exchange data between slaves
- IP channel for on demand transfers (optionnal)
  - Base on IP
  - Permet to exchange data between master and slaves
    - Operator display data, files, configurations, …
  - Exchange between slaves
  - Transparent communication with standard Ethernet nodes (PC, …)

SERCOS III – cycle

- Up to 4 Master Data Telegrams
- Up to 4 AT Device Telegrams
- A number of IP messages (max. duration)



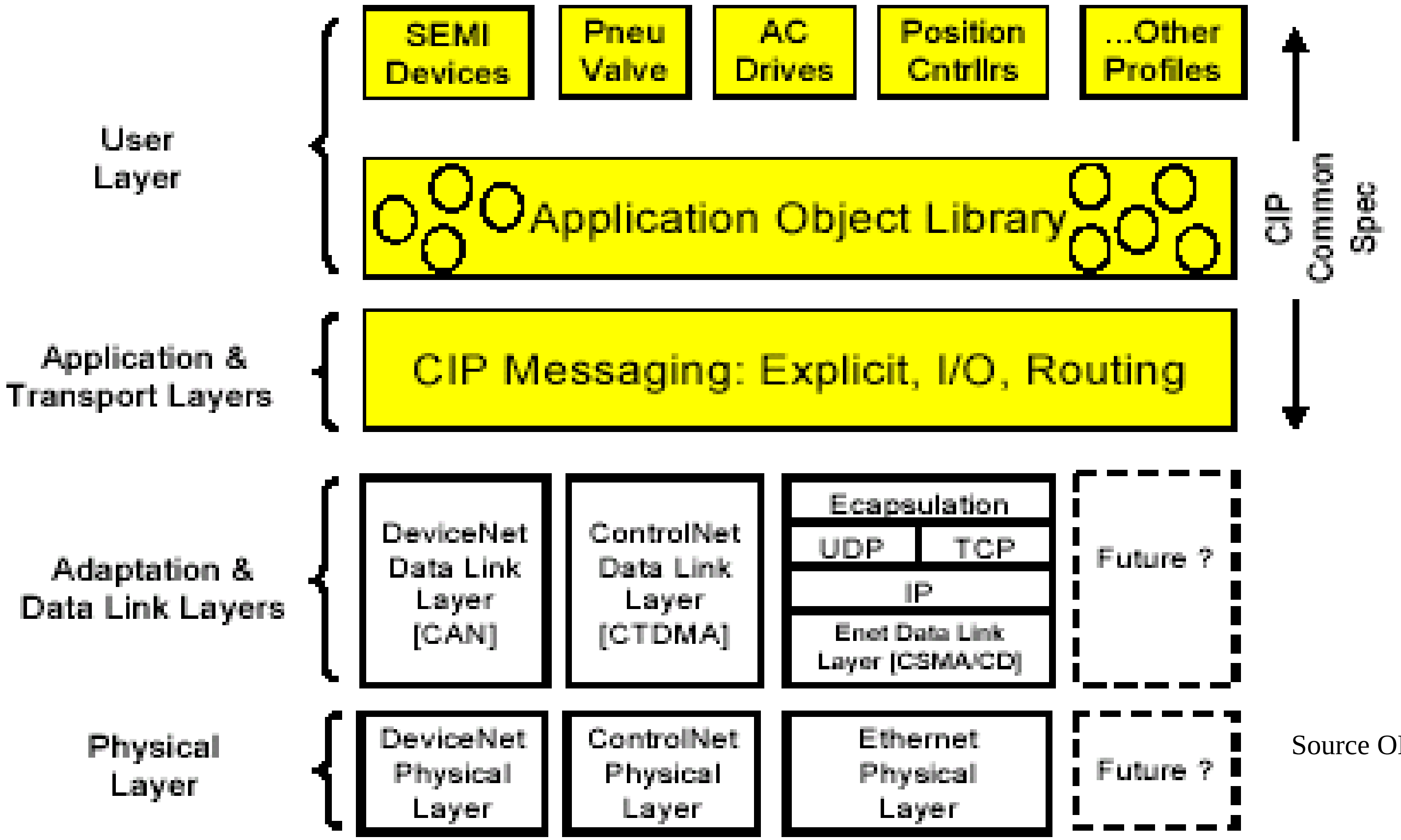
SERCOS III - analysis

- Advantages
  - Efficient / possibility of line topology
  - hotplug
  - Redundancy capability
  - A node may be hooked to a regular Ethernet network (one port must be left open)
  - Guranteed cycle time and reduced jitter
  - Uses regular IP frames (no encapsulation)
- Drawbacks
  - Protected by patents
  - Requires non standard hardware
  - Real-time behavior impossible in presence of non compliant nodes
  - Requires a bridge to regular Ethernet

Ethernet IP with time synchronization

- No limit in node number
  - Topology according to Ethernet
- No modification to 802.3
  - It is possible to use 802.1p priorities
  - Synchronisation according to IEEE 1588
- Compliant with IEEE 802.3u Fast Ethernet
  - IP based protocols are supported (TCP, UDP,...)
  - Implementation on standard 802.3 hardware
- Integration with CIP for compatibility with DeviceNet and ControlNet
- Node to node communication along a producer/consumer model

Ethernet IP



Source ODVA

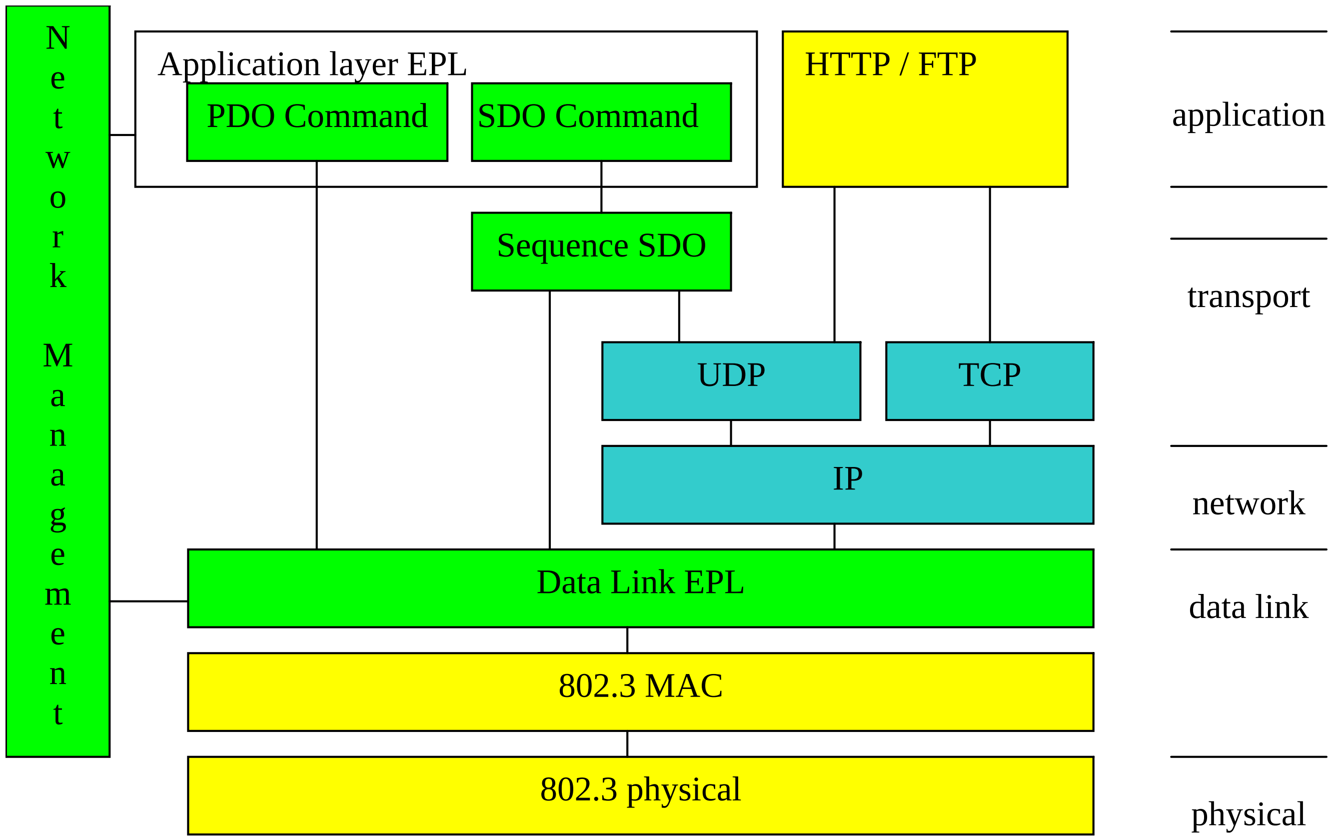
Ethernet IP - analysis

- Advantages
  - Standard hardware
  - Most of the used protocols are standard
  - Can be mixed with « pure » Ethernet nodes
  - Compatibility with DeviceNet and ControlNet
  - Synchronisation based on IEEE 1588
- Drawbacks
  - Cycle time is not constant, jitter is not controlled
  - Only statistical guarantees
    - Using priorities in switches
    - Filtering external traffic

Ethernet Powerlink in short

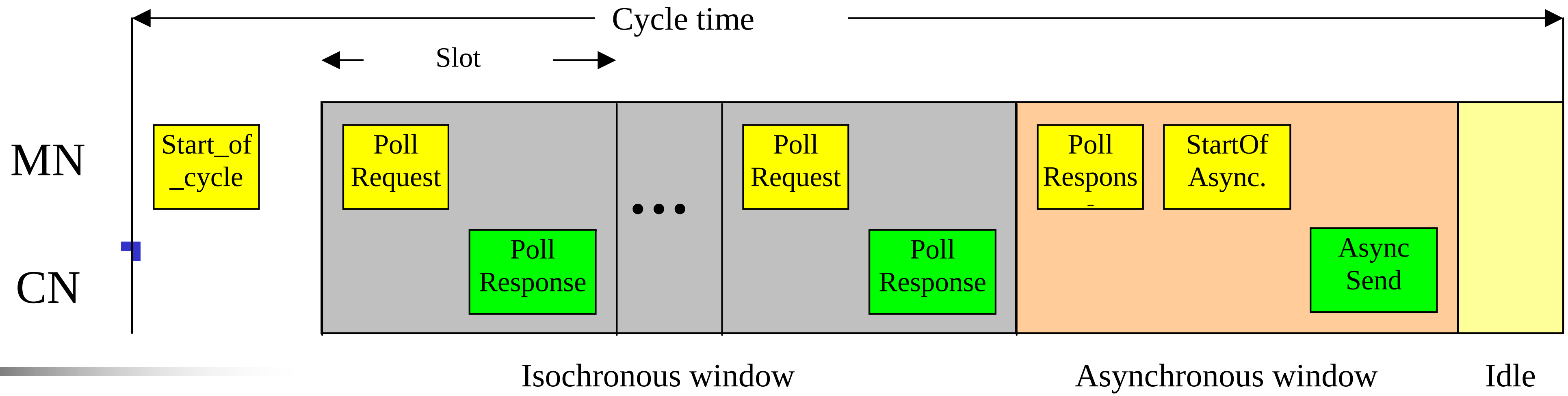
- Up to 240 nodes on a segment
  - Topology according to Ethernet + line topology possible
- So-called « guaranteed and deterministic communication »
  - Cycle time from 200µs
  - jitter <1µs for precise node synchronisation
  - IAONA real-time class 4 (highest performance one)
- Compliant with IEEE 802.3u Fast Ethernet
  - IP based protocols are supported (TCP, UDP,...)
  - Implementation on regular 802.3 hardware
- Integration with CANopen EN50325-4 for interoperability
- Node to node communication along a producer/consumer mode

Ethernet Powerlink – Model



Ethernet Powerlink – cycle

- Synchronous part made of slots
  - Continuous: CN is polled at each cycle
  - Multiplexed: a given CN is polled every n cycles
  - Synchronous exchanges
    - Sequence of PollRequest followed by PollResponse
    - Response is sent in broadcast (available to all)
      - Producer -> consumer
- Idle part (to keep a constant duration to the cycle)



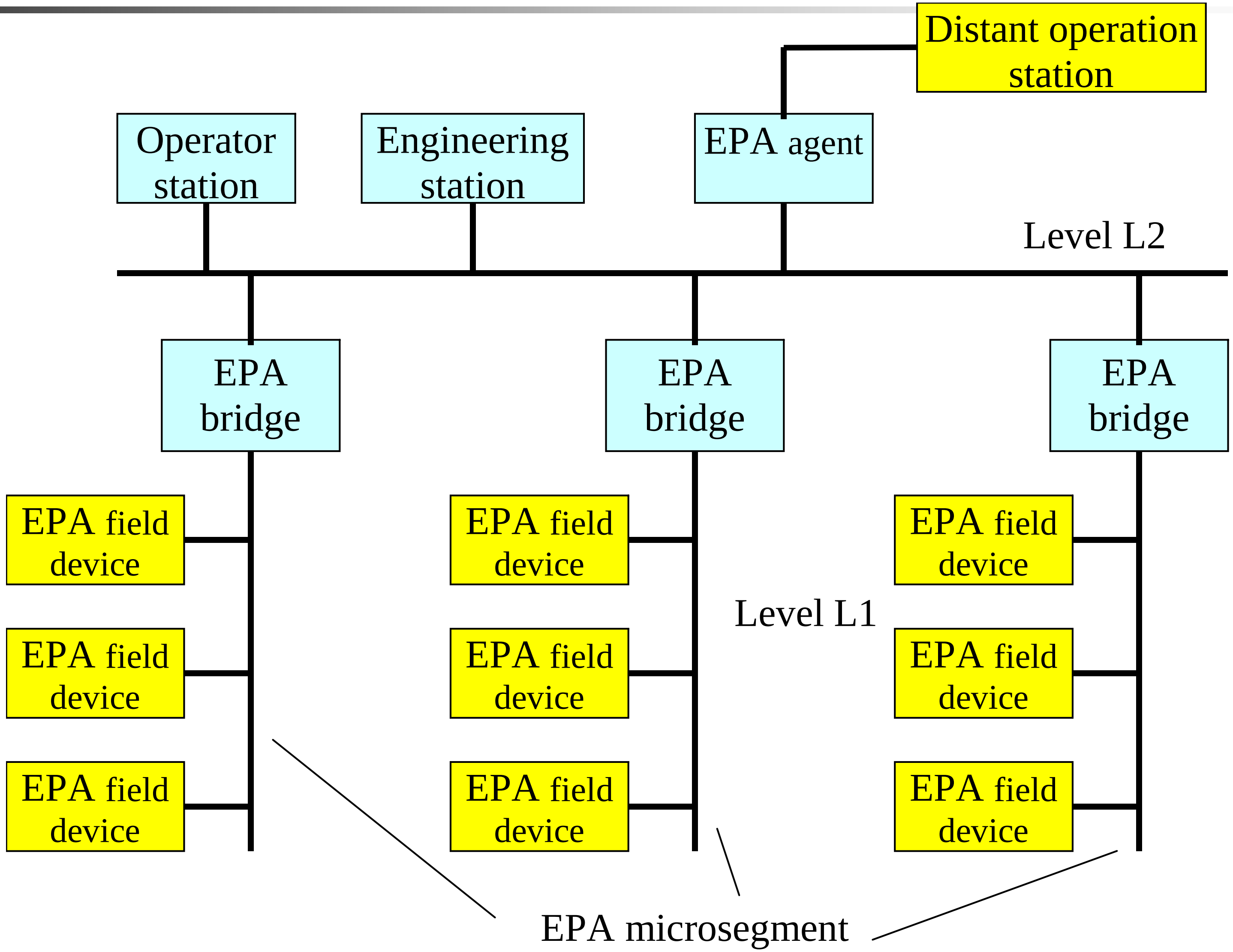
Ethernet Powerlink - Analysis

- Advantages
  - Constant cycle duration (in absence of error)
  - Line topology possible
  - Presence of an application layer
- Drawbacks
  - Only contains a limited subset of the necessary concepts (cf. WorldFIP)
  - Low efficiency (25µs lost in each transaction)
  - Cannot coexist with regular Ethernet nodes
  - Requires specialy designed routers and hubs
  - Model does not take errors into account
  - Quite sensitive to timing errors (collisions !)

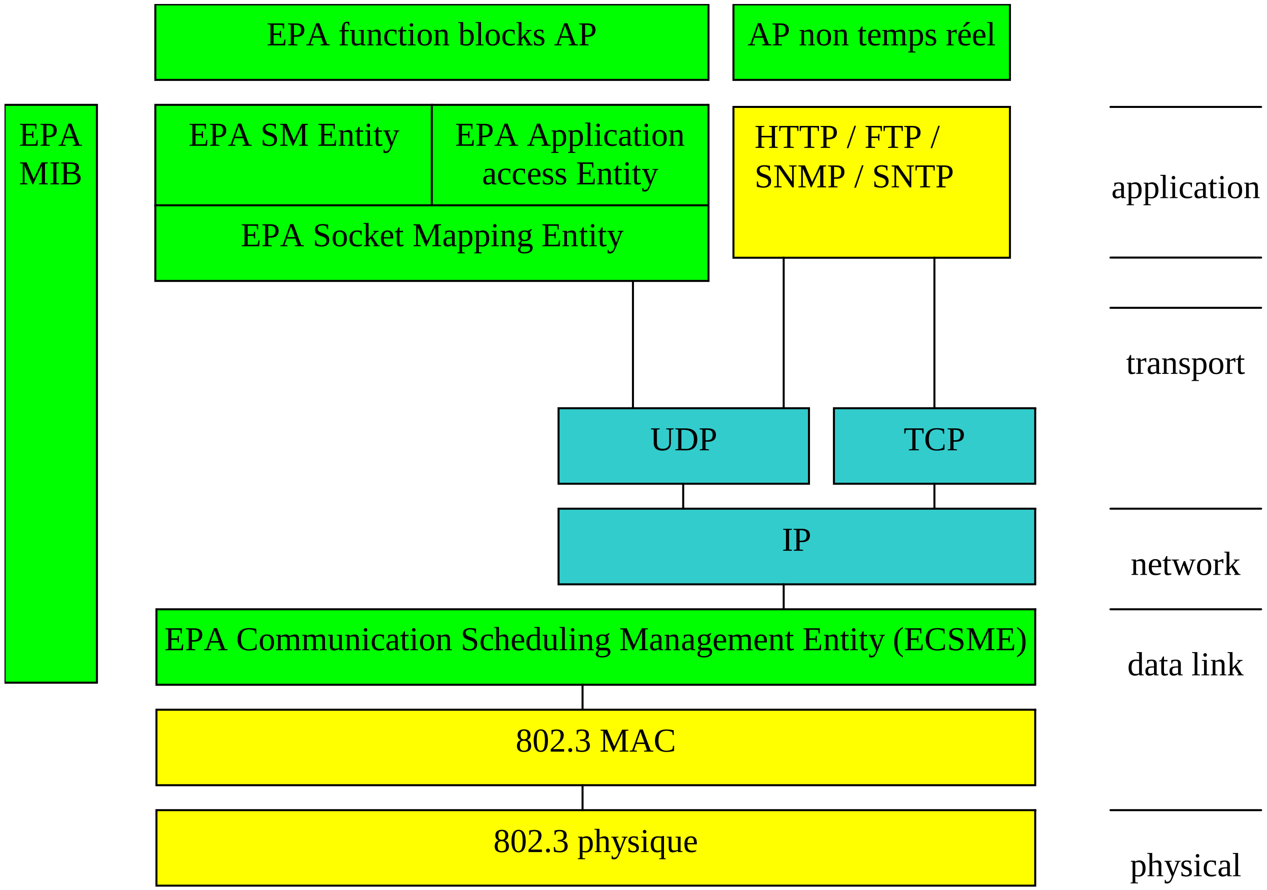
Real-Time Ethernet EPA - Ethernet for Plant Automation – in short

- Number of nodes only limited by physical considerations
  - Topology according to Ethernet (switch and hub)
- So-called « guaranteed and deterministic communication »
  - Cycle time in multiples of milliseconds
  - jitter depends on the selected IEEE 1588 class
- Compliant with IEEE 802.3 (all variants)
  - IP based protocols are used (TCP, UDP,...)
  - Implementation on regular 802.3 hardware
- Based upon IEEE 1588 for clock synchronisation
- Device capabilities described in XML
- Conventional client-server communication model
  - Process variables communicated according to IEC 61499 and IEC 61804 (function blocks)

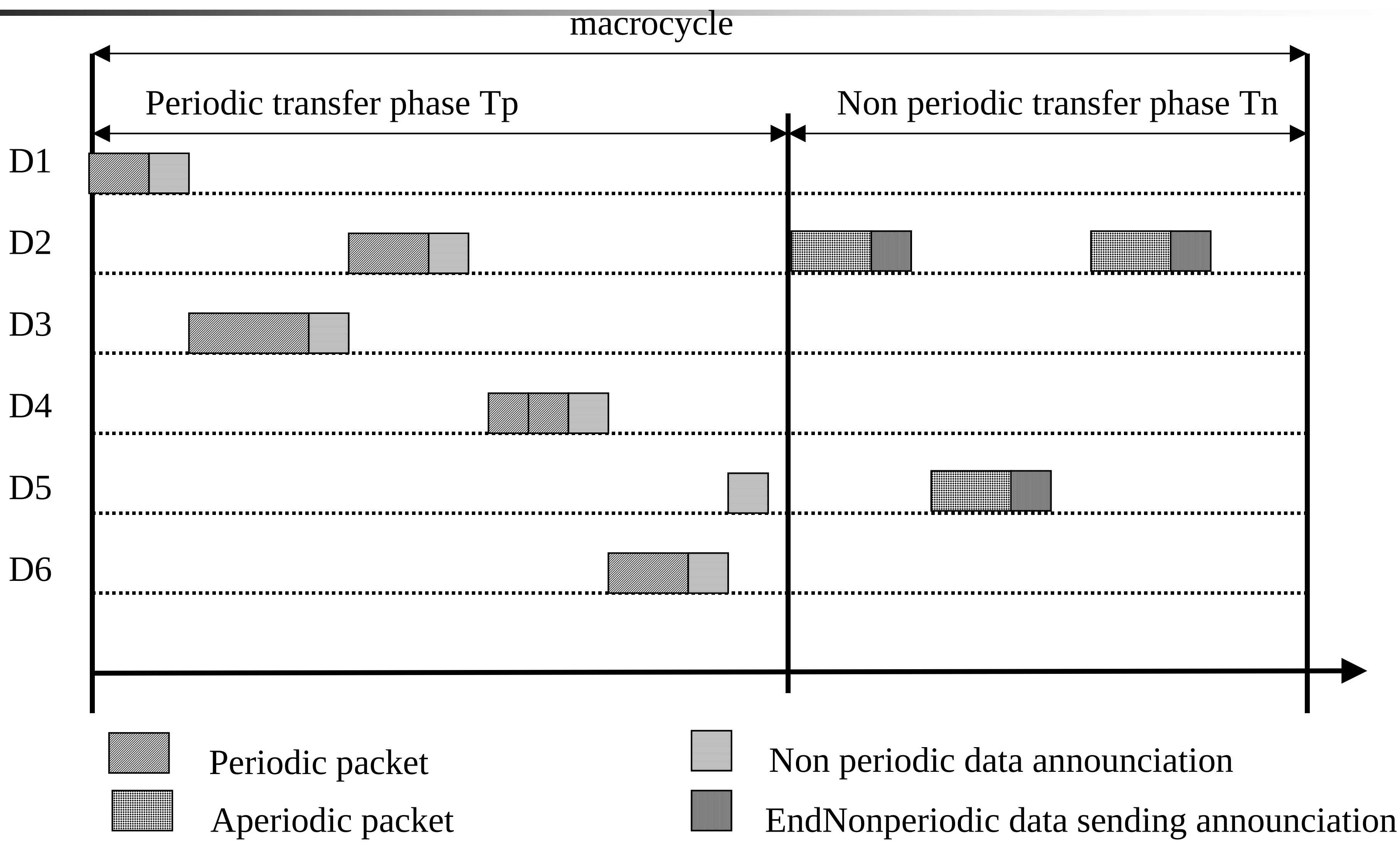
EPA – Topology



Real-Time Ethernet EPA - architecture



EPA - scheduling



Real-Time Ethernet EPA - analysis

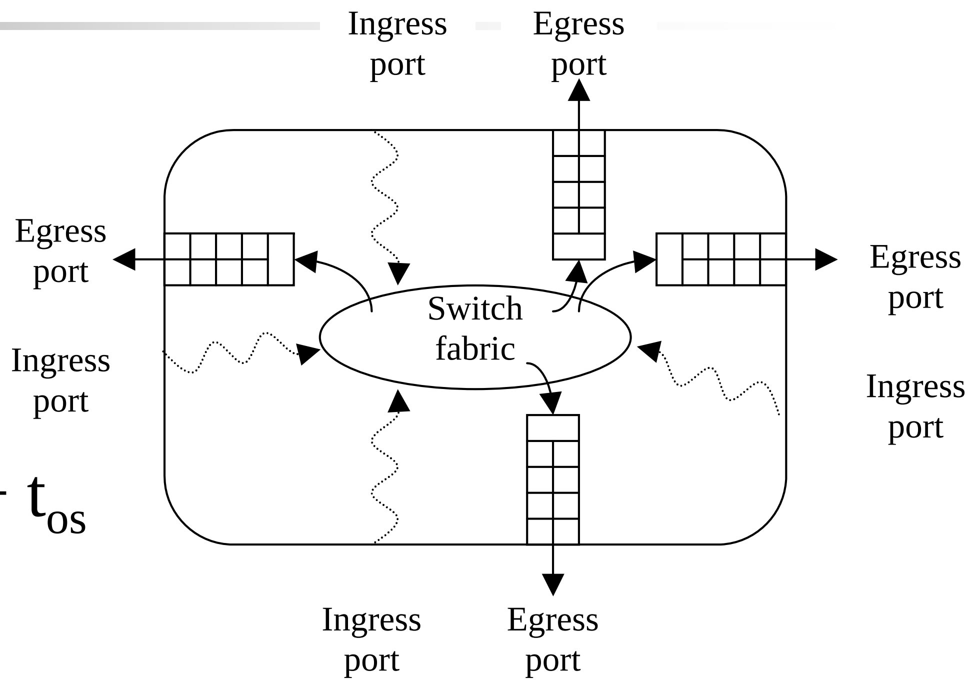
- Advantages
  - Support functional blocks
  - suitable application layer
- Drawbacks
  - Only client-server
  - Single polling cycle
  - Difficult to calculate guarantees (even in absence of error)
  - Some parts of the standard are quite obscure
  - Configuration must be centralized
    - To ensure that parameters are compatible and consistent

Others

- Standards
  - Profinet
    - V3 introduced real-time guarantees
  - AFDX Avionics Full Duplex Switched Ethernet
  - P-NET on IP
    - PNET is a virtual token MAC
    - Same on IP without any guarantee
  - Real-Time publish-subscribe
    - Just a publish subscribe layer on top of TCP without any guarantee
  - MODBUS on TCP/IP
    - Nothing real-time, just the protocol on top of TCP
  - Vnet/IP
    - Based on temporal windows / Proposed by Yokogawa (www.yokogawa.com/us)
  - Time Critical Control Network
- Non standard (so far): TT-Ethernet

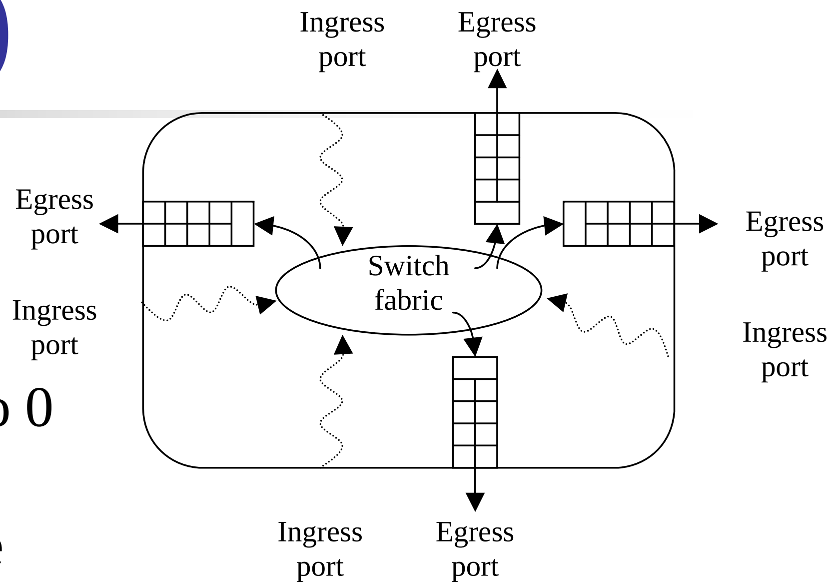
Switched Ethernet

- Temporal definitions
  - t_{mux} : multiplexing delay
  - t_{queue}: queueing delay
  - t_{trans} : packet transmission delay = $t_{frame} + t_{mux} + t_{queue} + t_{os}$
  - t_{os} : operating system delay
  - t_{frame}: frame tx delay
    - 121µs for 1514 bytes @ 100Mbit/s
- How to calculate the delay ?
  - Use of the network calculus



4 port switch

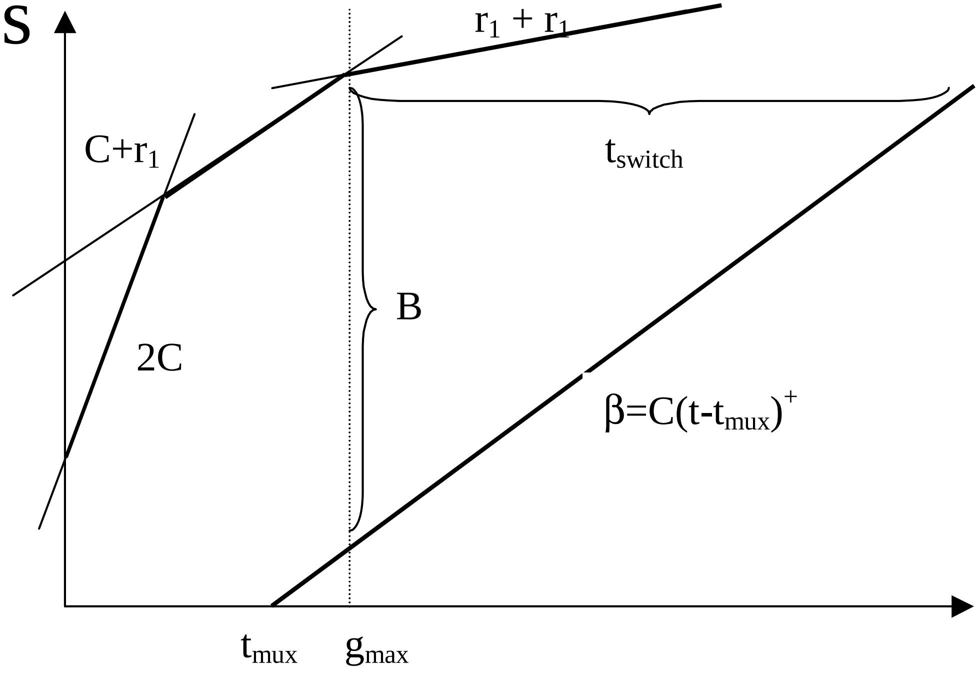
Switched Ethernet (2)



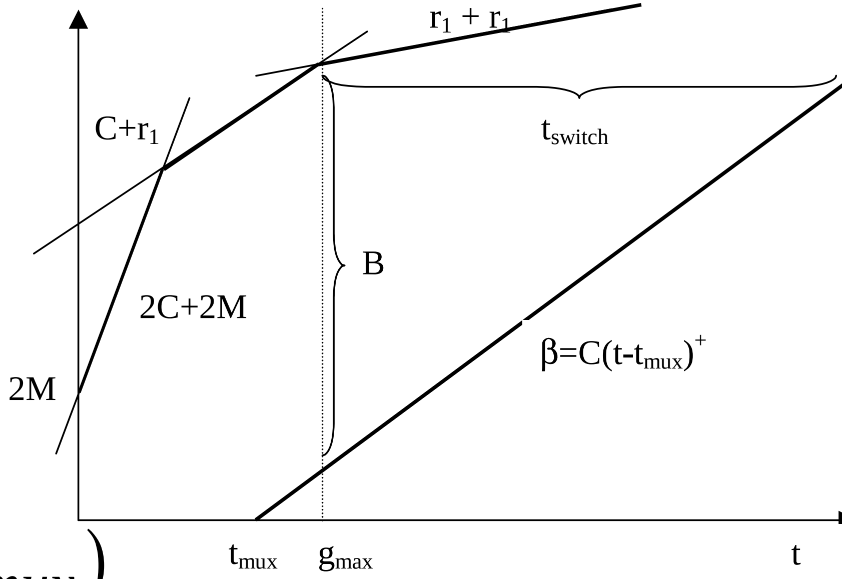
- Let us look at one output port
  - Service curve $\beta(t) = C\,(t-t_{mux})+$
    - + means that the function is equal to 0 for $t-t_{mux} < 0$
    - C is the maximum transmission rate on the output port
  - Arrival curve
    - Sum of arrival curves of all incoming traffic whose destination is that output port
    - One station on each ingress port : $\alpha(t) = \min\,[Ct + M, r_k t + b_k]$
      - M maximum frame size
      - r_k long term average rate ($\Sigma\, r_k \leq C$ should hold for output)
      - b_k burstiness of the traffic ($M < b_k$ and $r_k \leq C$)

Switched Ethernet (3)

- Case of 2 incoming traffics
  - Maximum backlog = max. vertical distance between arrival and service curves
  - Maximum delay (FIFO order) = max. horizontal deviation between arrival and service curves



Switch backlog (FIFO order)



- Inflexion point

$$g_i = \frac{b_i - M}{C - r_i}$$

- Backlog

$$B = \sum_{k=1}^{N} b_k + \sum_{k=1}^{N} r_k g_{\max} - C\left(g_{\max} - t_{mux}\right)$$

$$B = \sum_{k=1}^{N} b_k - g_{\max}\left(C - \sum_{k=1}^{N} r_k\right) + Ct_{mux}$$

- Backlog estimation

$$B_{est} = \sum_{k=1}^{N} b_k + Ct_{mux}$$

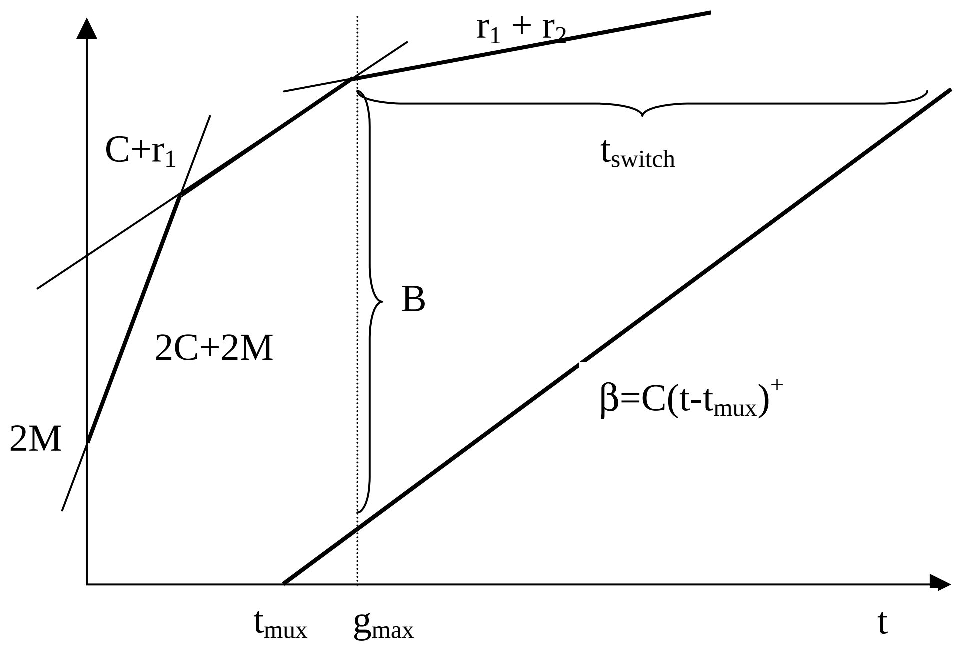
Switch delay (FIFO order)

- Distance at g_{max}
- Delay

$$t_{switch} = \sum_{k=1}^{N} \frac{b_k}{C} - g_{\max}\left(1 - \sum_{k=1}^{N} \frac{r_k}{C}\right) + t_{mux}$$

- Can be approximated

$$t_{est} = \sum_{k=1}^{N} \frac{b_k}{C} + t_{mux}$$

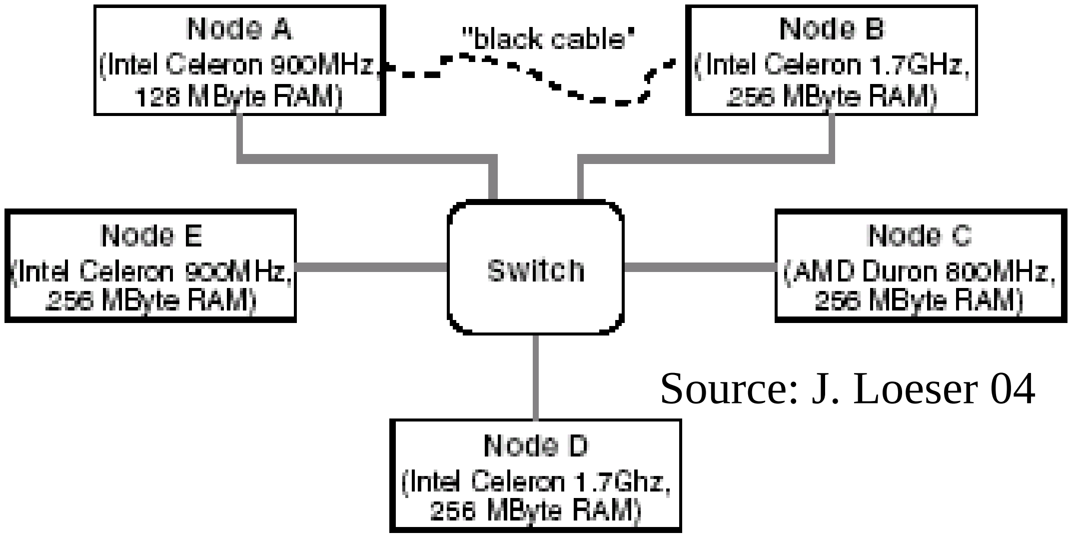


Remarks

- Arrival curve implies traffic shaping
  - This can be done using the token bucket algorithm
    - Bucket size b (If token arrives when the bucket is full, it is discarded)
    - Fill rate r (1 token is added to the bucket every 1/r seconds)
      - Alternately S tokens added every S/r seconds
    - Maximum packet size M
    - When a packet of n bytes arrives, n tokens are removed from the bucket, and the packet is sent to the network (waits otherwise).
- Backlog is per egress queue
  - Is a way to calculate necessary buffer size
- Analysis is valid for one switch (May be extended)

Measurement setup

- 3 different switches
  - 3Com office connect
  - Level-One FSW-2108TX
  - Intel Netstructure 470F
- NIC
  - Intel EEPro/100
  - 3Com 3C985B-SX
- Delays measured from with min. size frames on UDP



Source: J. Loeser 04

Switch buffer size

- Measured by sending bursts of traffic
  - Increasing burst length until missing frames
  - Using network calculus to derive buffer size

Switch	# 1514 byte frames	Size [Kbyte]
100M 3Com	14	20.5
100M level-One	87	127.4
1000M Intel	200	293

Source: J. Loeser 04

Influence of shaping interval

- Bucket size: $b = r\,T_s + M$

Node	C (40MB/s)	D (32MB/s)	E (20MB/s)
T_s = 10ms	51514 bytes	41514 bytes	26514 bytes
T_s = 1ms	6515 bytes	5514 bytes	4014 bytes
T_s = 0.1ms	2014 bytes	1914 bytes	1764 bytes

Source: J. Loeser 04

- CPU usage

Node	C (40MB/s)	D (32MB/s)	E (20MB/s)
T_s = 10ms	4.1%	2.9%	2.3%
T_s = 1ms	11%	9%	7.2%
T_s = 0.1ms	21.2%	17.2%	11.9%

Buffer bounds and delays

- Packet transmitted from A to B

	buffer bound	t_{max}	t_{est}	t_{obs} max.
T_s = 10ms	111.8 KB	9.357 ms	9.731 ms	8.759 ms
T_s = 1ms	15.7KB	1.38 ms	1.345 ms	1.3 ms
T_s = 0.1ms	6.1 KB	0.582 ms	0.506ms	0.438 ms

Source: J. Loeser 04

Analysis of the experiment

- Max. bandwidth on a link 98.6 Mb/s
- Experiment used 92 Mb/s ≈ 93% link use
  - Max. delay from 0.58ms, 1.4 ms to 9.4 ms at 100 Mb/s
  - Requires traffic shaping
- Results valid
  - for a single switch
    - Must be adapted for cascaded switches (traffic shapes)
  - For FIFO behavior
  - Provided all nodes play the game

Can be extended to multiple switches, see J. Specht, S. Samii, Urgency-Based Scheduler for Time-Sensitive Switched Ethernet Networks, ECRTS 2016, pp.75-85

Conclusion

- Vintage Ethernet was not so bad
- Switched Ethernet
  - Gives the possibility to use up 100% of the bandwidth
    - With switches that have large enough buffers
    - With traffic shaping
    - Provided all nodes stick to the traffic shaping rules
  - Is not so good in terms of topology
  - Still suffer from delay variations

The solution ?

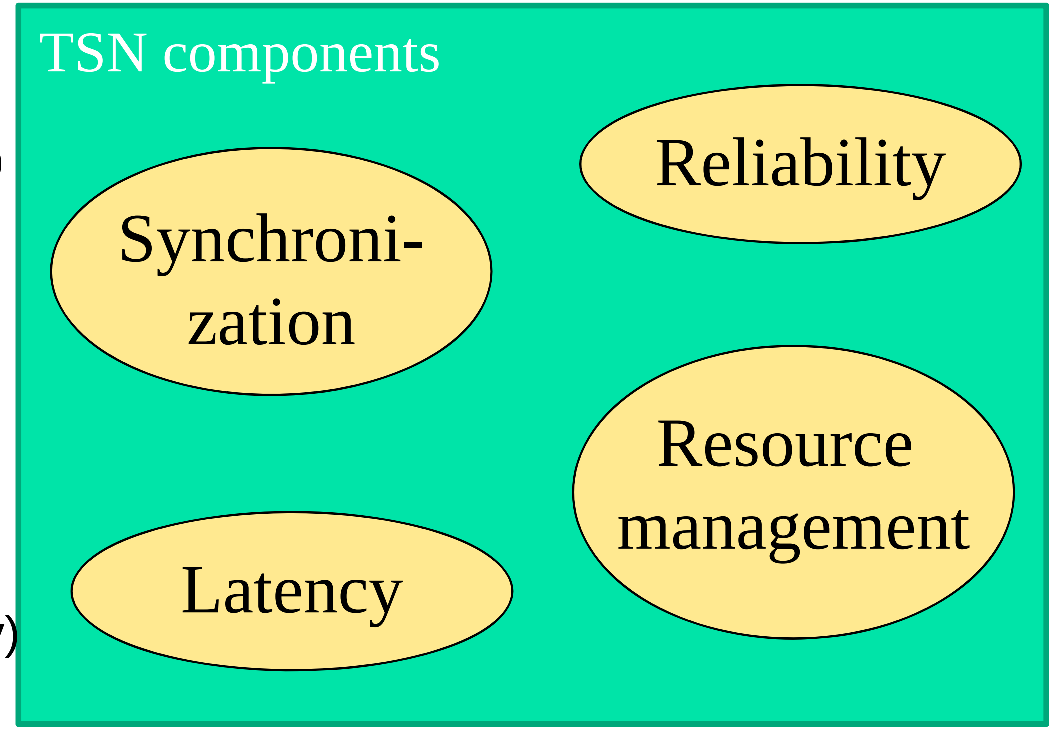
- For satisfying real-time constraints
  - Switched Ethernet
  - Use of message priorities in switches (IEEE 802.1Q)
  - Traffic smoothing / shaping
  - IEEE 1588 for clock synchronization
- Look at IEEE Time Sensitive Networking group (https://en.wikipedia.org/wiki/Time-Sensitive_Networking)
- Security: 802.1x, IPSec, SSL
- Application layer (MMS or similar)

Work on Ethernet

- Still an active subject of research
  - Mainly studying the switch scheduling policies and the corresponding schedulability analysis
- Improving the standard
  - Time Sensitive Networking working groups under the IEEE 802.1 project
    - See next slide
  - Audio Video Bridging (AVB)
    - Started in 2005. First efforts to bring real-time to standard Ethernet
      - See U. Bordoloi et al, Schedulability Analysis of Ethernet AVB Swiches, RTCSA 2014.
    - Now generalized and renamed to TSN

Time Sensitive Networking (TSN)

Timing and sync (802.1AS)



Frame replacement
& elimination (P802.1CB)
Path Control (802.1Qca)
Per-Stream Filtering
(802.1 Qci)
Time Sync (P802.1AS-Rev)

Preemption (802.1Qbu)
Scheduled traffic (802.1Qbv)
Cyclic queuing (802.1 Qch)
Asyn. Shaping (802.1Qcr)
Credit-based shaper (802.1 Qav)

Stream Reserv Prot
(802.1Qat)
TSN configuration
P802.1Qcc)
YANG (P802.1Qcp)
Link-local Reserv Prot
P802.1CS)

Standards for TSN (Time Sensitive Networking)

- IEEE Std 802.1Qbu-2016 - IEEE Standard for Local and Metropolitan Area Networks -- Bridges and Bridged Networks -- Amendment 26: Frame Preemption. It allows a Bridge Port to suspend the transmission of non time critical frames while one or more time critical frames are transmitted
- IEEE Std 802.1Qbv-2015 - IEEE Standard for Local and Metropolitan Area Networks -- Bridges and Bridged Networks -- Amendment 25: Enhancements for Scheduled Traffic. It specifies time aware queue draining to schedule the transmission of frames relative to a known time scale.
- • IEEE Std 802.1Qca-2015 - IEEE Standard for Local and Metropolitan Area Networks -- Bridges and Bridged Networks -- Amendment 24: Path Control and Reservation. It extends the application of Intermediate System to Intermediate System (IS-IS) to bridged networks in order to provide explicit trees for data traffic.

All 3 are now in IEEE Std 802.1Q-2018

AVB standards (Audio Video Bridging)

- IEEE Std 802.1AS-2011 - IEEE Standard for Local and Metropolitan Area Networks -- Timing and Synchronization for Time-Sensitive Applications in Bridged Local Area Networks. It provides a Layer 2 time synchronizing service that is appropriate for the most stringent requirements of consumer electronics applications.
- IEEE Std 802.1Qat-2010 - IEEE Standard for Local and Metropolitan Area Networks -- Virtual Bridged Local Area Networks - Amendment 14: Stream Reservation Protocol (SRP). Has been rolled into IEEE Std 802.1Q-2014.
- IEEE Std 802.1Qav-2009 - IEEE Standard for Local and Metropolitan Area Networks -- Virtual Bridged Local Area Networks - Amendment 12: Forwarding and Queueing Enhancements for Time-Sensitive Streams, which specifies the Credit Based Shaper. Has been rolled into IEEE Std 802.1Q
- • IEEE Std 802.1BA-2009 - IEEE Standard for Local and Metropolitan Area Networks -- Audio Video Bridging (AVB) Systems. It specifies a set of usage-specific profiles to help interoperability between networked devices using the AVB specifications.

TSN Standards under study

- P802.1CS – Link-local Registration Protocol
- P802.1DC – Quality of Service Provision by Network Systems
- P802.1DF – TSN Profile for Service Provider Networks
- P802.1DG – TSN Profile for Automotive In-Vehicle Ethernet Communications
- P802.1AS-Rev – Timing and Synchronization for Time-Sensitive Applications
- P802.1AX-Rev – Link Aggregation Revision
- P802.1ABcu – LLDP YANG Data Model
- P802.1CBcv – FRER YANG Data Model and Management Information Base Module
- P802.1CBdb – FRER Extended Stream Identification Functions
- P802.1CMde – Enhancements to Fronthaul Profiles to Support New Fronthaul Interface, Synchronization, and Syntonization Standards

TSN Standards under study (2)

- P802.1Qcj – Automatic Attachment to Provider Backbone Bridging (PBB) services
- P802.1Qcr – Bridges and Bridged Networks Amendment: Asynchronous Traffic Shaping
- P802.1Qcw – YANG Data Models for Scheduled Traffic, Frame Preemption, and Per-Stream Filtering and Policing
- P802.1Qcx – YANG Data Model for Connectivity Fault Management
- P802.1Qcz – Congestion Isolation
- P802.1Qdd – Resource Allocation Protocol

More info at https://1.ieee802.org/tsn/#Ongoing_TSN_Projects

References

- G. Held, « Ethernet networks », 4th edition, Wiley, 2003, ISBN 0-470-84476-0
- D. Boggs, J. Mogul, C. Kent, “ Measured Capacity of an Ethernet : myths and reality “, in Proc. SIGCOMM’88, Stanford, Ca, Aug.16-19, 1988, pp.222-234.
- A. Tanenbaum, « Networks », 4e ed., Pearson, ISBN 2-7440-7001-7
- J. Loeser, H. Haertig, « Low-latency Hard real-time communication over switched Ethernet », Proc. ECRTS 04, Catania, It., pp. 13-22.
- J.-D. Decotignie, « Ethernet Based Real-Time and Industrial Communications », Proc. of the IEEE, Vol. 93 (6), June 2005
  - Look at the references given in the paper

Information Sources

- Modbus (www.modbus.org) specs are online
- P-Net
- Ethernet Powerlink (www.ethernet-powerlink.org) few docs
- EtherCat (www.ethercat.org) some brochures
- Profinet (www.profibus.com)
  - PROFINET, « PROFINET CBA Architecture Description and Specification », Version 2.02, May 2004
- Ethernet IP (www.ethernet-ip.org)
- SERCOS (www.sercos.de)
- Fachhochschule Reutlingen website has a lot of information (www-pdv.fh-reutlingen.de/rte)