TIMICO

Real-time Ethernet

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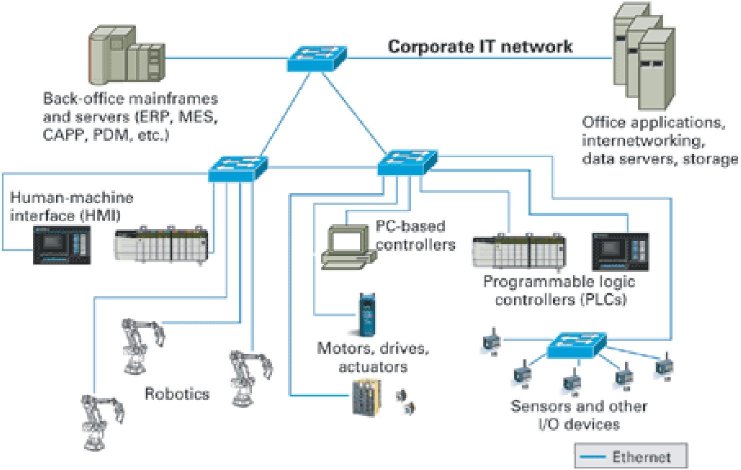
Outline

Outline

Ethernet moves to the plant floor



Typical network requirements

Plant networks may span entire production facilities

- Connecting various nodes: office servers ↔ sensors/actuators

Control networks typically span plant floor

- Connecting specialized nodes

Device networks typically span parts of plant floor

- Connecting sensors and actuators

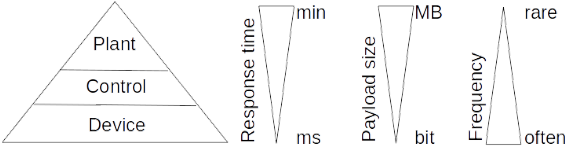


Figure : Typical network requirements at plant, control, and device levels

Ethernet convergence

Convergence in hardware and software standards

- More companies to support development
- All benefit from all
- Unifies and simplifies the wealth of field-buses
- Ubiquity reduces R&D, production, training, and maintenance costs
- Open standards may progress initiatives in open source projects and small/medium sized companies
- Get all the benefits of prior Ethernet R&D efforts for free

The OSI reference model

About the model

OSI (Open Systems Interconnection) model (ISO/IEC 7498-1)

- ISO: International Standards Organization
- IEC: International Electrotechnical Commission

Not a network architecture per se

- Comprises seven abstraction layers for communication
- Does not precisely specify services and protocols in each layer
- Just tells **in general** what each layer should do
- A layer serves the layer above it

Quite similar to the TCP/IP reference model

- Not a network architecture per se either

The OSI reference model

Ethernet's place in the model

	Layer	Data unit	Name	Function
Host layers	7	Data	Application	Meaning of data
	6		Presentation	Data representation and en/de-cryption. Machine de/inde-pendent data conversion
	5		Session	Interhost communication
	4	Segments	Transport	End to end connection, reliability and flow control
Media layers	3	Packet or datagram	Network	Determination of data paths within the network via logical addressing
	2	Frame	Data link	Data transmission via physical addressing, source, destination, and checksum
	1	Bit	Physical	Media (wire/fiber), signal connection, voltage levels, and binary transmission

Ethernet frame

Ethernet, IEEE 802.3

The OSI reference model

Communication in the model

- A layer serves the layer above it, i.e. layer L_n serves L_{n+1}
- Service Data Units (SDU) are passed down from L_{n+1} to L_n
- L_n encapsulates L_{n+1} SDUs into protocol data units (PDU)
- A L_{n+1} SDU is embedded in the payload of a L_n PDU
- SDU is data sent by a user of the services of a given layer, and is transmitted semantically unchanged to a peer service user
- L_n entity peers interact by the L_n protocol by transmitting PDUs

Ethernet frame structure

- Payload includes all other protocol headers and footers
- Payloads less than 46 octets are padded
- 802.1Q for VLAN and quality of service prioritization
- **Video (5:23): Renepick, How to build an Ethernet Frame, 2013**

Preamble	Start of frame delimiter	MAC destination	MAC source	802.1Q tag (optional)	Ethertype (Ethernet II) or length (IEEE 802.3)	Payload	Frame check sequence (32-bit CRC)	Interframe gap
7 octets	1 octet	6 octets	6 octets	(4 octets)	2 octets	42[note 2]–1500 octets	4 octets	12 octets
		64–1522 octets						
72–1530 octets								
84–1542 octets								

Figure : 802.3 Ethernet frame structure (Wikipedia).

Protocol overhead and efficiency

Ethernet protocol efficiency $= \frac{\text{Payload size}}{\text{Frame size}}$

- Good (nearly best) case: $\frac{1500\text{octets}}{1542\text{octets}} = 97.28\%$
- Bad (nearly worst) case: $\frac{46\text{octets}}{1542\text{octets}} = 2.98\%$

Other protocol headers in Ethernet payload, e.g.

- $\approx$ 8 (LLC) + 20 (IP) + 20 (TCP) = 48 octets

E.g. add 48 header octets to send 10 yields 58 octets ($>$ 46)

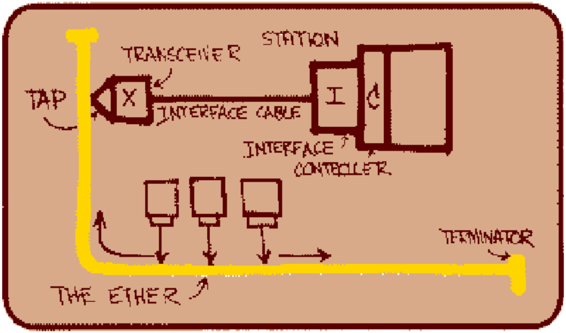
- Efficiency from payload perspective $\frac{10\text{octets}}{1542\text{octets}} = 0.65\%$

Ethernet timeline

- 1973: First versions of Ethernet developed at Xerox PARC
- 1975: Patent on Ethernet was filed by Xerox
- 1976: Ethernet deployed at PARC
- 1980: DIX (Digi. Equip. Corp/Intel/Xerox) std. v.1: 10 $\frac{\text{Mbit}}{\text{s}}$
- 1980: IEEE began R&D on LAN std. 802
  Different specs were promoted, e.g. CSMA/CD by DIX, Token Ring by IBM, Token Bus by GM
- 1985: IEEE std. 802.3 CSMA/CD was published. HDX
- 1990: In the decade, Ethernet became prevalent LAN tech.
- 1998: IEEE 802.3x introduced FDX
- 2011: Ethernet ubiquitous in home/industry: 0.1 and 1 $\frac{\text{Gbit}}{\text{s}}$

Ethernet layout anno 1976

Robert Metcalfe presents Ethernet to the National Computer Conference in June 1976



Video (9:14): The History of Ethernet, R. Metcalfe, 2007

Ethernet physical media examples

The original commercially available variant of Ethernet – no longer in use

10BASE5 (ThickNet)

- Coaxial cable with 9.5 mm diameter and 50Ω impedance
- Throughput of **10** Mbit/s
- **Base**band digital transmission
- Maximum segment length of **5**00 m
- Maximum 100 nodes per segment

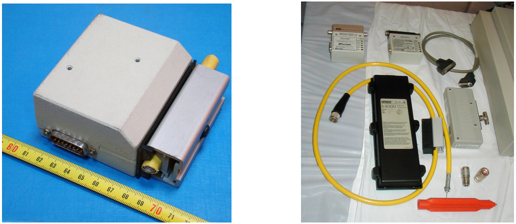


Figure : Transceivers, cables and tapping tool (Wikipedia)

Ethernet physical media examples

Other media examples

10BASE2 (ThinNet)

- Coaxial
- As 10BASE5 but cheaper and easier to install

10BASE-T (UTP)

- Full-duplex **U**nshielded **T**wisted **P**air
- Revision IEEE 802.3i completely new physical layer
- Also: 100Base-T/TX and 1000Base-T

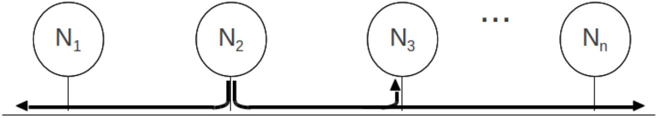
10BASE-FL

- Full-duplex fiber-optic cable
- Also: 100Base-FX & 1000BASE-SX/LX

Outline

Single segment Ethernet

- Originally single segment and HDX (< ca. 1990)
- CSMA/CD for sharing bandwidth on shared medium
- Speed is function of no. of simultaneously active nodes
- Collisions reduce throughput
- Packets are received by all. NIC filters per address
- During transmission: 1 node/time exclusive right to medium
- Damage to shared medium affects entire segment



CSMA/CD - Carrier Sense

Carrier Sense Multiple Access with Collision Detection

- Network interface card (NIC) listens for traffic on bus
- If traffic exist: Do not transmit
- If no traffic for a certain period (inter-frame gap): Transmit

CSMA/CD - Multiple Access

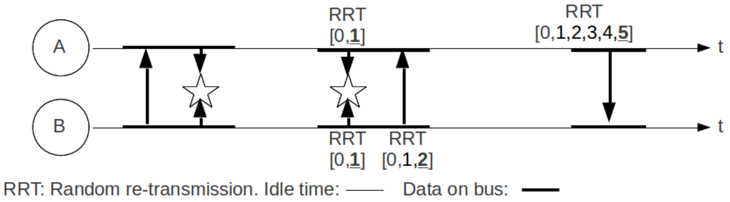
Carrier Sense Multiple Access with Collision Detection

- Multiple nodes on shared medium
- Collisions are highly likely
- All packets are passed by all nodes
- NIC filters: only addressee nodes receive data

CSMA/CD - Collision Detection

Carrier Sense Multiple Access with Collision Detection

- Collision occur if nodes send data simultaneously
- Nodes monitor own transmission
  - If node detects collision (high voltage signal)
  - Transmission stops and jam-signal broadcasted
  - Nodes discard packets and stops transmitting



CSMA/CD - Collision Detection

Carrier Sense Multiple Access with Collision Detection

Truncated binary exponential back-off algorithm

- To schedule retransmissions after detected collision
- Retransmit after a random number of slot-times:
  Max theoretical roundtrip time: $t_{\text{slot}} = t_{\text{data out}} + t_{\text{jam back}}$
- Back-off after $c \in [1; c_{\text{max}}]$ collisions: $t_{\text{back-off}} = r \cdot t_{\text{slot}}$
- Where
  - $r \sim \mathcal{U}[0, ..., 2^c - 1]$ where $\mathcal{U}$ is the uniform PMF
  - $t_{\text{slot}} = 51.2\mu$s at 10 Mbit/s
  - $t_{\text{slot}} = 5.12\mu$s at 100 Mbit/s
- Truncated means
  - Ceiling on retransmission timeout
  - IEEE 802.3 CSMA/CD standard: $c_{\text{max}} = 10$ (IEEE, 2008 [3])
  - Transmission canceled after 16 successive attempts and back-off interval reset to initial value

Medium monopolization by back-off algorithm

- Two nodes A and B have a number of packets to transmit
- At some point a collision occur and, e.g. B randomly selects 0 and A selects 1 in [0;1]
- Thus B will be successful in first retransmission
- B still has more packets to send and tries immediately to send again. By chance this collides with A
- A doubles the back-off interval whereas B uses the initial one. Thus B has higher chance of transmitting successfully
- This may repeat and B may monopolize the medium

Summary of single segment Ethernet

Pros in regard to real-time operations

- Low cost, flexible, and ubiquitous hardware

Cons in regard to real-time operations

- CSMA/CD w/ random back-off algorithm
- Nondeterministic medium access timing makes it hard to guarantee deadlines
- No packet prioritization means that time-critical packets may yield for non-critical packets

Perspectives

- Methods to counter the cons exist

Outline

Motivation and background

Single segment Ethernet

Multi segment Ethernet

Single segment real-time Ethernet

Multi segment real-time Ethernet

References

Main functionalities of a switch

Micro-segmentation

- Separate collision domain for each network segment
- Only two nodes coexist in a collision domain
- Nodes have dedicated point-to-point bandwidth
- Full duplex without collisions

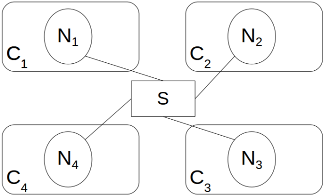
Figure : Industrial Ethernet switches from Molex

Micro-segmentation by switch

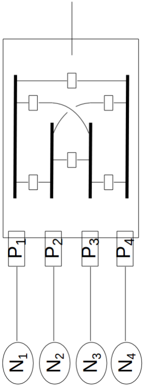
Single segment vs. switched Ethernet

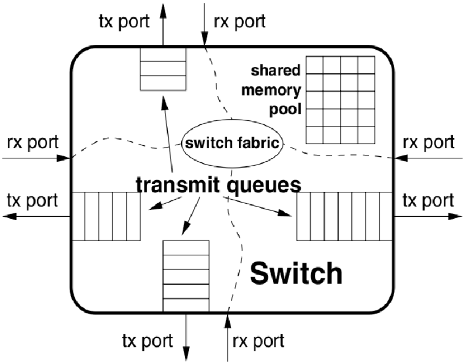
- One collision domain, C, for multiple nodes, N
- Collisions are possible
- Non-deterministic

- One collision domain, C, per node, N, due to switch, S
- Collision free
- Deterministic



Conceptual switch internals





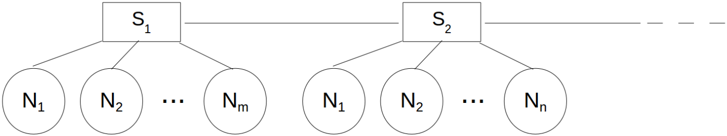
Switched Ethernet

Fully switched means full-duplex Ethernet

- Collision-free: Only 2 nodes per collision domain
- Net speed is x bit/s $\Rightarrow$ node-to-node is 2x bit/s

Cabling

- Twisted-pair or fiber optic
- Separate transmit (Tx) and receive (Rx) conductors



Switching methods on port basis

Store and forward

- Entire packets buffered and checksum verified
- Corrupted packets dropped

Cut through

- Reads only up to destination address before forwarding
- Forwards corrupted packets as checksum is not verified
- Higher speed than store and forward

Adaptive switching

- If error rates low: Cut-through mode
- If error rates high: Store-and-forward mode

Characteristics of switched traffic

Corruption

- Bit errors by noise or interference
- Drops and retransmits packets in store and forward

Latency

- Communication delay in media, e.g. wires, switches, routers
- Delay may build up even if throughput is approx. constant
- `Ping` command measures round-trip (NOOP) latency

Packet delay variation (PDV)

- Low PDV: RT system may deal with latency by time offsets
- High PDV: Unpredictable and hard to guarantee deadlines

Latency and packet loss example

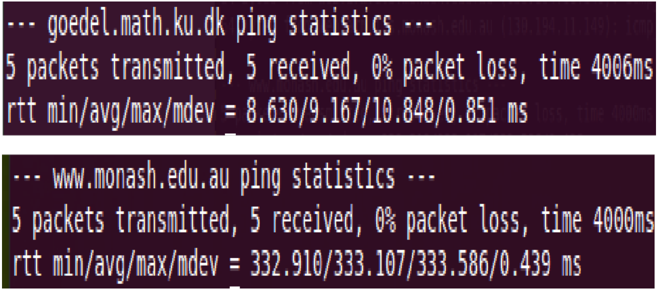


Figure : `Ping` statistics

Typical switch data

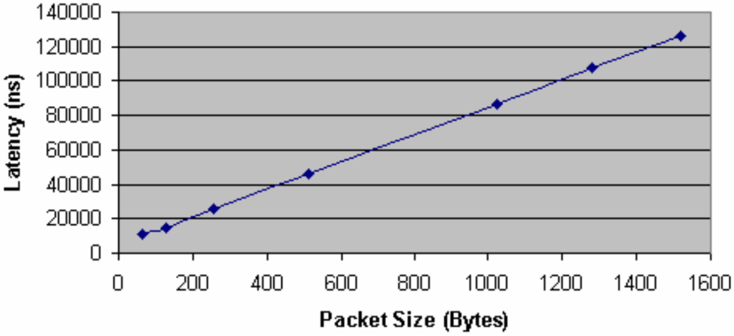
Port to port communication

- Less than 50 μs
- Depends on packet size

Packet delay variation

- Approximately 100 ns

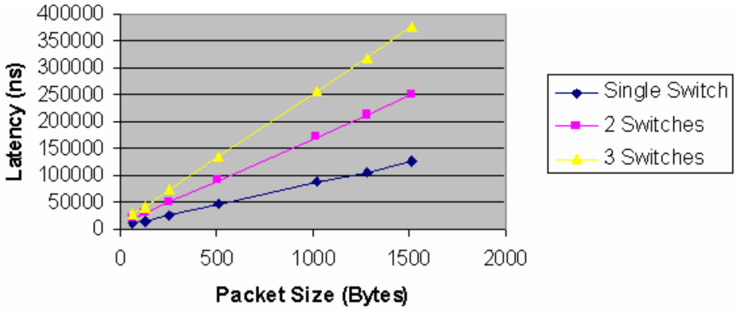
Latency: Single 100Mbit/s switch



- Min: (packet size, latency) = (64 Bytes, 10840 ns)
- Max: (packet size, latency) = (1518 Bytes, 126240 ns)

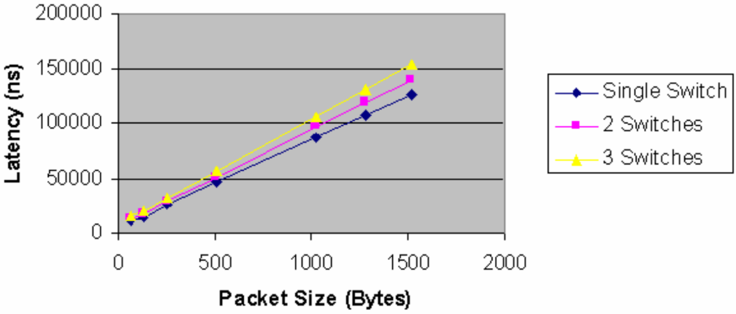
(Coley, 2004 [1])

Latency: Multiple 100Mbit/s switches



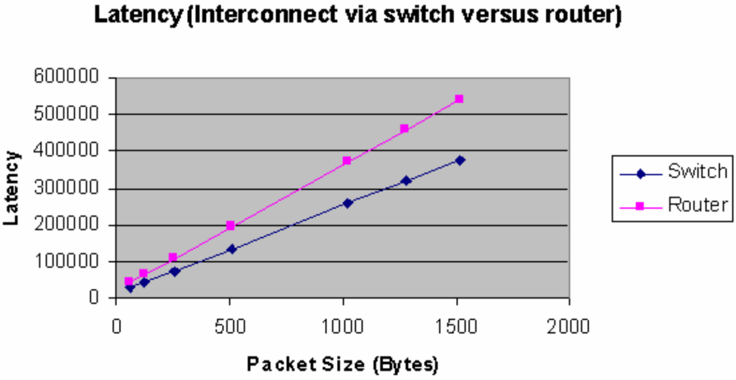
(Coley, 2004 [1])

Latency: Multiple Gbit/s switches



(Coley, 2004 [1])

Latency: Connecting two switches



- Routers read the address for proper routing

(Coley, 2004 [1])

Nagle's algorithm

Increases bandwidth at the expense of latency

- Combines outgoing packets with small payloads
- Decreases overhead/pay-load ratio
- Good for normal Ethernet operations

Poor compliance with real-time systems

- Increases latency and packet delay variations

Disable / enable the algorithm

- Disable it: TCP_NODELAY socket option
- E.g. Unix nc6 (netcat): Swiss army knife for TCP, UDP, ...
- "Client": nc6 –disable-nagle -l -p 1234
- "Server": nc6 127.0.0.1 1234

Summary of multi segment Ethernet

Pros in regard to real-time operations

- Fully switched gives full duplex
- No collisions: only two nodes in same collision domain
- Network segmentation via logical overlay virtual LAN
- Low cost, flexible, and ubiquitous hardware

Cons in regard to real-time operations

- Deadlines hard to guarantee
- Arrival times of packets hard to predict
- Ethernet frames vary in size
- Unknowns: Route, latency, packet delay var., corruption ratio

Perspectives

- Methods to counter the cons exist

Outline

Single segment real-time Ethernet approaches

Main challenge

- Collision avoidance on shared medium

Common approaches

- Token based
- Time slot based
- Statistics based

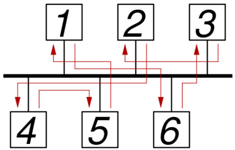
See (Moraes, 2010 [4]) for a survey on real-time in CSMA networks

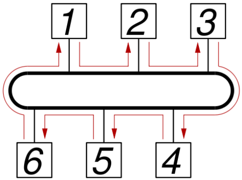
Single segment real-time Ethernet

Token based

Token represents permission to transmit

- Token circulated according to strategy
- Token management uses time and bandwidth
- Only one node may transmit at any time
- Limited performance vs. switched networks





Single segment real-time Ethernet

Time slot based

Time slot represents permission to transmit

- Time is divided according to strategy (TDMA)
- Strike a balance on time-slot lengths
  - Long: Long idle periods. Short: Frequent data partitioning
- Time management uses time and bandwidth
- Limited performance vs. switched networks

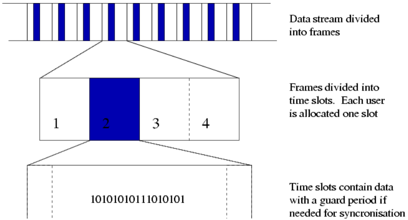


Figure : Stream into frames and time slots with data+guard (Wikipedia)

Single segment real-time Ethernet

Statistical based

- Keep network traffic low to bound probability of collisions
- Statistical guarantee to nodes for transmission time and bandwidth
- The overall network utilization decreases with stronger statistical guarantees
- Basically avoidance of invoking the back-off algorithm

Outline

Motivation and background

Single segment Ethernet

Multi segment Ethernet

Single segment real-time Ethernet

Multi segment real-time Ethernet

References

Multi segment real-time Ethernet approaches

Main challenge

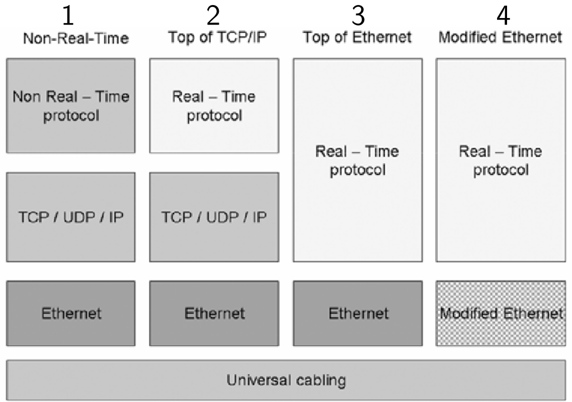
- Bandwidth control and scheduling, e.g. in switches

Common approaches

- ProfinetIRT
- EtherCAT
- Ethernet Powerlink
- Sercos III
- EtherNet/IP

Classification of multi segment RTE approaches

By protocol stacks

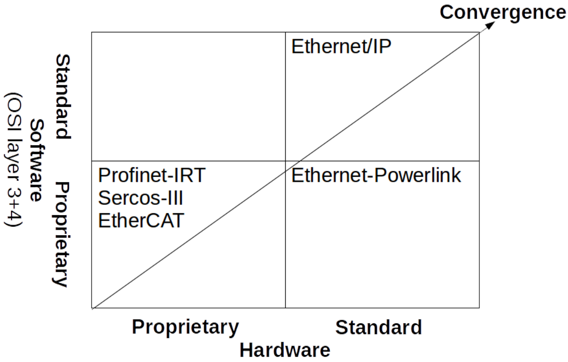


(Felser, 2005 [2])

1. No RTE overlay
2. Ethernet/IP
3. Ethernet Powerlink
4. Profinet v3, Sercos-III, EtherCAT

Classification of multi segment RTE approaches

By hardware and software compliance



Classification of multi segment RTE approaches

By bandwidth control methods

Separate slave polling

- Ethernet Powelink, ProfiNet IRT, Sercos-III

Combined slave polling

- EtherCAT

Time based

- Ethernet/IP (based entirely on standard Ethernet)

Ethernet Powerlink, ProfiNet IRT, and Sercos III

Separate slave polling

Per cycle

- RT traffic: Master polls each slave with an Ethernet telegram
- Non-RT traffic: Remaining cycle time

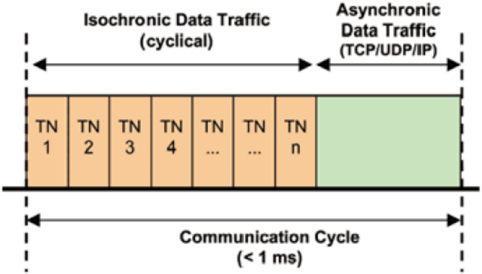


Figure : Time slot mechanism

Ethernet Powerlink, ProfiNet IRT, and Sercos III

Separate slave polling

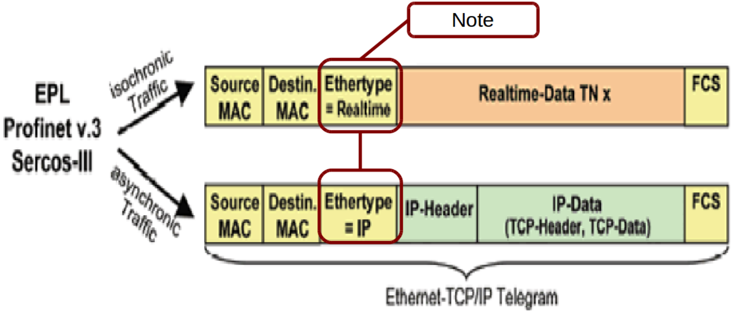


Figure : Telegram structuring

Ethertype

- ID of protocol encapsulated in the Ethernet frame payload

EtherCAT

Combined slave polling

Per cycle

- RT traffic: Master polls slaves with an Ethernet telegram shared by all
- Non-RT traffic: Space reserved as a sub-telegram in the shared telegram

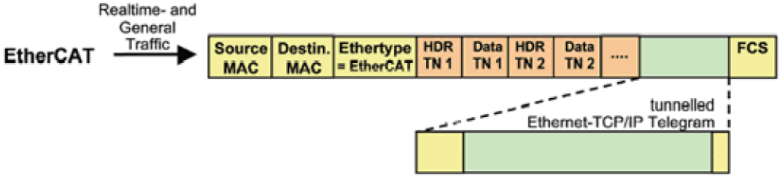


Figure : Telegram structuring

EtherCAT

Combined slave polling

- Designed for small payloads per node
- One Ethernet frame holds more sub-frames
  - Encoded and decoded by special hardware
  - Slaves read and write in same sub-frame on the fly
- Each with payloads for nodes in the network
  - Reduces overhead/payload ratio
- Synchronization via distributed clock
  - Very low packet delay variations

EtherNet/IP

Time based

Ethernet/IP

- Based entirely on standard Ethernet
- Synchronized clocks via Precision Time Protocol
- Control commands must be received by slaves in due time
- RT delivery by master by UDP
- QoS prioritization of traffic (802.1Q)

EtherNet/IP

Time based

Preamble	Start of frame delimiter	MAC destination	MAC source	802.1Q tag (optional)	Ethertype or length	Payload	Frame check sequence (32-bit CRC)	Interframe gap
7 octets of 10101010	1 octet of 10101011	6 octets	6 octets	(4 octets)	2 octets	46–1500 octets	4 octets	12 octets

Figure : QoS prioiritization in Ethernet frame; switches prioritize traffic

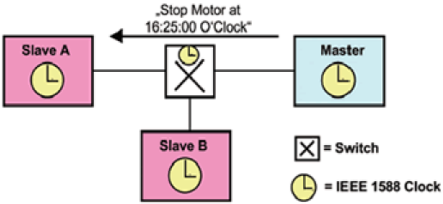


Figure : Precision Time Protocol for clock synchronization

Comparison of approaches in real-time setup

- Setup: 100 axles to be controlled synchronously
- Response time: Cycle time
- Jitter: Variations in response time
- Conclusion: More proprietary → Faster and less jitter

Organization	Response time (for 100 axles)	Jitter	Data rate
Ethernet/IP CIPSync ODVA	≈1ms	<1ms	100Mbit/s
Ethernet Powerlink EPSG	<1ms	<1ms	100Mbit/s
Profinet-IRT PNO	<1ms	<1ms	100Mbit/s
Sercos-III IGS	<0.5ms	<0.1ms	100Mbit/s
EtherCAT ETG	≈0.1ms	<0.1ms	100Mbit/s

Comparison of approaches in real-time setup

- Setup: Field bus vs. Ethernet
- No. of slave pollings measured in no. of packets/ms
- Performance criteria: Theoretical packet throughput (actual throughput lower due to processing and latency)
- Conclusion: New Ethernet based systems perform well

	Transfer rate	Packet size *with 8 bytes of user data*	Theoretical packe throughput
Profibus DP	12 Mbit/s	19 bytes	79 packets/ms
Sercos-II	16 Mbit/s	14 bytes	142 packets/ms
Ethernet	100 Mbit/s	72 bytes	174 packets/ms

Outline

Further reading

Online material

- Industrial Ethernet University
- Industrial Ethernet Book
- IEEE Standards Association
- ODVA (Open DeviceNet Vendors Association)
- Ethernet Powerlink Standardization Group
- EtherCAT Technology Group
- Fieldbus Foundation
- Modbus Organization
- Profibus and Profinet International
- Sercos – The Automation Bus

Further reading

Papers and books

- Snader, J.C., "Effective TCP/IP Programming", Addison Wesley, 2000
- Lammermann, S., "Ethernet as a real-time technology", Univ. of Telecomm., Leipzig, 2008
- Marx, U. and RTnet development team, "RTnet project", Univ. of Hannover, Germany, 2011

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[3] IEEE (2008). IEEE 802.3-2008, part 3: Carrier sense multiple access with collision detection (CSMA/CD) access method and physical layer specifications. Rev.: 3rd printing 22 June 2010. URL: http://standards.ieee.org/about/get/802/802.3.html. pp. 1-315.

[4] Moraes, R. (2010). Survey of real-time communication in CSMA-based networks. In *Network Protocols and Algorithms*, Volume 2.