Università degli Studi di Padova

MIME
Master's degree ICT Internet Multimedia Engineering

Department of Information Engineering (DEI)
Master degree on ICT for Internet and Multimedia Engineering (MIME)

Internet of Things and Smart Cities
10 – IoT technologies (wired)

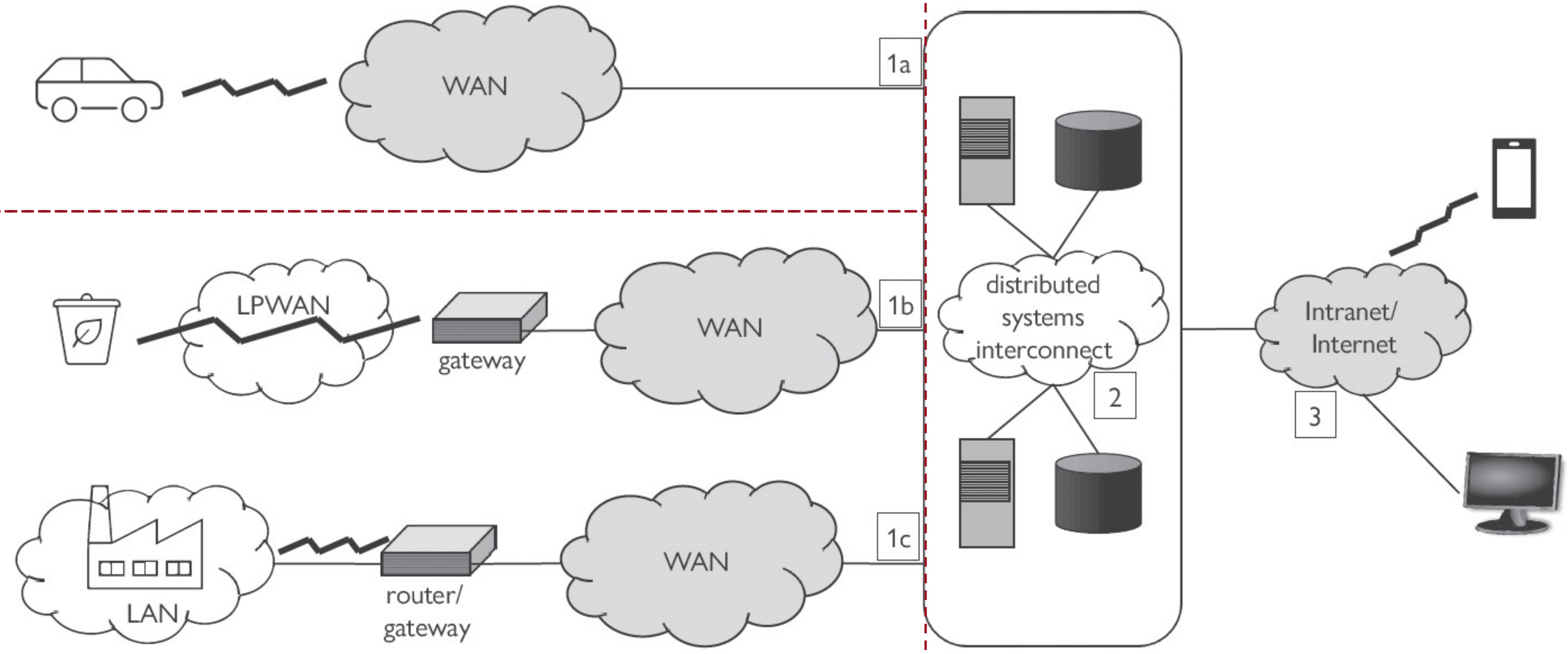
Marco Giordani (marco.giordani@unipd.it)
Department of Information Engineering (DEI) – SIGNET Research Group
University of Padova – Via Gradenigo 6/B, 35131, Padova (Italy)

Do you remember?

Network architectures

One-level architecture

Two-level architecture



Introduction

Motivations

- Main (surviving) wired communication technology: **Ethernet**.
- Ethernet is an interesting technology also to implement industrial networks.
  - Cost redutions enabled by large production scales.
  - Easy availability of skilled personnel.
  - Possibility to have unique and homogeneous network technology.
- Still, some modifications are needed to enable Ethernet in the industrial domain, also referred to as “**Industrial Ethernet**” or **Real-Time Ethernet (RTH)**.
- Notable example of RTH standards: Powerlink, **EtherCAT**, Profinet, etc.

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10 – IoT technologies (wired)

Ethernet (review)

Marco Giordani (marco.giordani@unipd.it)
Department of Information Engineering (DEI) – SIGNET Research Group
University of Padova – Via Gradenigo 6/B, 35131, Padova (Italy)

Ethernet

Introduction

- Ethernet: it is the name given to the data-link layer communication protocol described in the **IEEE 802.3 standard**.
- Developed in the 1970s by Robert Metcalfe and David Boggs.
- Approved and standardized in 1980-81 by the consortium of companies named DIX (Digital Corporation, Intel Corporation, Xerox Corporation).
- Standardized in 1983 as IEEE 802.3 (approved by ISO as ISO 8802.3)
- Since its early stage, Ethernet it has gone through **four generations**.

Standard 10 Mbps	**Fast** 100 Mbps	**Gigabit** 1 Gbps	**10-Gigabit** 10 Gbps

Ethernet

Services

- The **Ethernet service** is:
  - Connection less (a frame is sent whenever ready).
  - No flow control.
    - Sender can overwhelm receiver with frames.
    - Excess frames are silently dropped.
    - Loss recovery is delegated to upper layers.
- No ACK (frames do contain a 32-bits CRC (or FCS) field for error detection but ARQ is not natively implemented at MAC layer for bit errors: if CRC fails, the frame is silently dropped by the receiver
- Retransmission in case of collision → CSMA/CD.

Ethernet

Frame structure

- 802.3 and Ethernet have very minor differences.
  - The **Type** field in Ethernet has been replaced with a 2-byte **Length** field in IEEE formats.

IEEE 802.3

7	1	6	6	2	0-1500	4	
Sync	SD	Destination	Source	**Length**	802.2 frame +PAD	FCS	

Ethernet

7	1	6	6	2	0-1500	4	
Sync	SD	Destination.	Source	**Type**	Payload + PAD	FCS	

Ethernet

Frame size

- The frame size of Ethernet is limited between **64 bytes** and **1518 bytes.**
  - 18 bytes are for header and trailer: payload is between **46 bytes** and **1500 bytes.**
- **Why a maximum frame length?**
  - Avoid one station monopolizes the bus for a long time
  - Bound the packet error probability: If I lose the packet, just retx it.
  - Reduce buffering requirements (back in the ’80, memory was expensive!).
- **Why a minimum frame length?**
  - Reducing overhead? But then what if just one byte is transmitted?
  - MAC mechanism: **CSMA/CD**.

Ethernet

Frame size

MAC mechanism: **CSMA/CD**.

- Transmission of a frame of size S with bitrate C takes time $T_{fr} = S/C$.
- For collision detection, it must be $T_{fr} > 2T_p \rightarrow S > C \cdot 2T\_p$.
- Signal propagation speed over cable is c = $2 \cdot 10^8$ m/s.
- Max cable length is $d = 2500$ meters (imposed by network designers).
- C = 10 Mbps (standard speed at the time).
- $T_p = d/c = 12.5$ μs.
- CONSTRAINT on transmission time for CSMA/CD: $T_{fr} \geq 2T_p = 25$ μs.
- $T_{fr} = S/C \rightarrow S_{min} = C \cdot T_{fr} = 10$ Mbps $\cdot$ $25\,\mu s$ = 250 bits ≅ **31.25 B.**
- Considering the additional delays due to repeaters and a certain safety margin, the minimum length is set to **64 B**.

Ethernet

Implementations

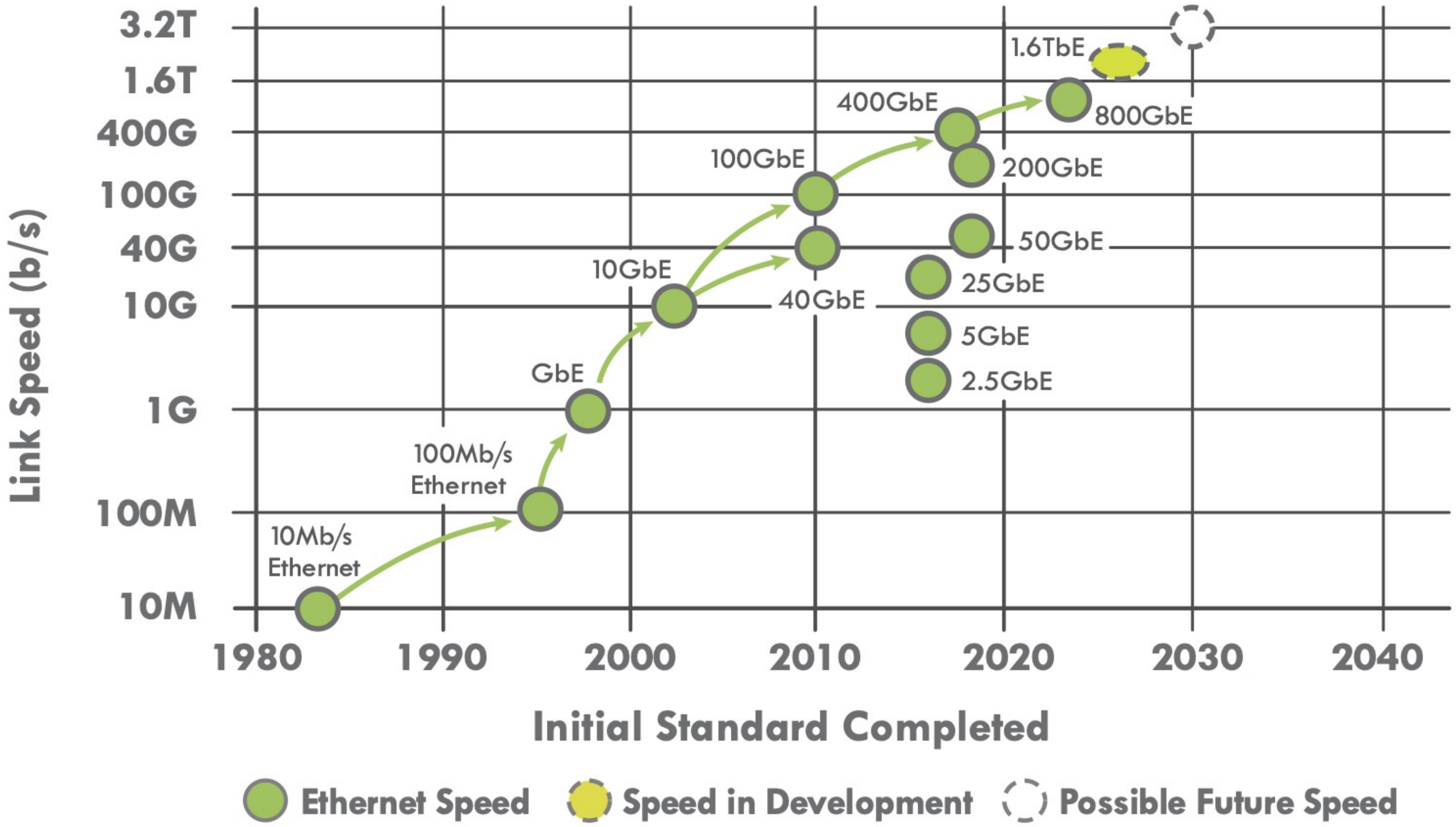
X | BASE | -Y
Data rate | Baseband | Cable lenght/type

Specification	Year	Speed
100BASE-TX	1995	100 Mbit/s
100BASE-T1	2015	100 Mbit/s
100BASE-FX	1995	100 Mbit/s
100BASE-T	1999	100 Mbit/s
1000BASE-T1	2016	1 Gbit/s
1000BASE-LX	1998	1 Gbit/s
1000BASE-RHx	2017	1 Gbit/s
1000BASE-PX	2004	1 Gbit/s
10GBASE-T	2006	10 Gbit/s
10GBASE-PR	2009	10 Gbit/s
10GBASE-LR	2002	10 Gbit/s
100GBASE-LR1	2021	100 Gbit/s

Ethernet

Implementations

Ethernet Alliance 2024 Roadmap:
https://ethernetalliance.org/wp-content/uploads/2024/03/2024-Ethernet-Roadmap-Digital-Version-March-2024.pdf



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10 – IoT technologies (wired)
Industrial Ethernet

Marco Giordani (marco.giordani@unipd.it)
Department of Information Engineering (DEI) – SIGNET Research Group
University of Padova – Via Gradenigo 6/B, 35131, Padova (Italy)

Industrial Ethernet

Introduction

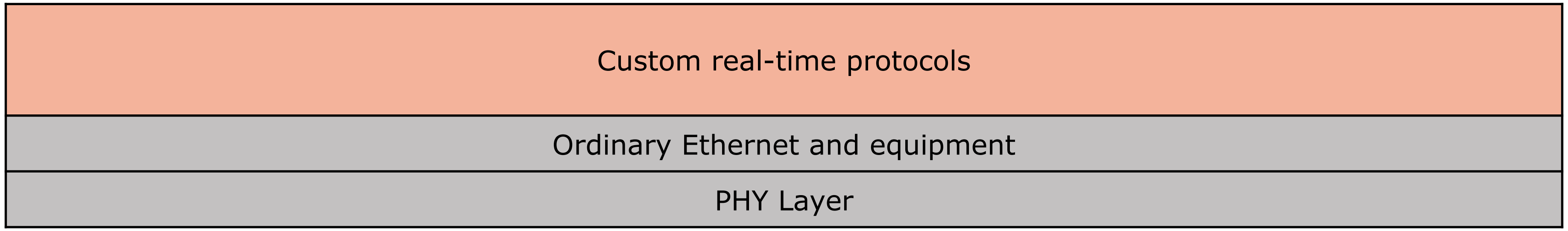
- Some modifications are needed to enable Ethernet in the industrial domain, also referred to as "**Industrial Ethernet**" or **Real-Time Ethernet (RTH)**.
  - In particular, Ethernet is not deterministic, and may not support **real-time operations.**
- 3 classes:
  - **Class 1**: Ordinary Ethernet + TCP/IP stack
    - Full compatibility with Ethernet/IP networks.
    - "Soft" real-time (with loose requirements: latency ≥ 100 ms).
    - Unpredictable delay due to other possible traffic flows.

Custom real-time protocols
TCP/UDP/IP
Ordinary Ethernet and equipment
PHY Layer

Industrial Ethernet

Introduction

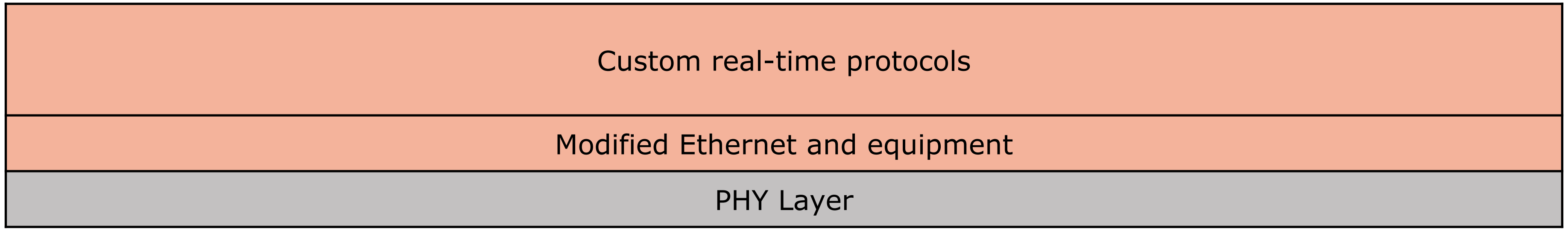
- 3 classes:
  - **Class 2**: Ordinary Ethernet + custom apps
    - Runs a specially designed real-time protocol stack on the Ethernet layer (latency ≥ 10 ms).
    - Some protocol modifications are required to support real-time (e.g., IEEE 1588 PTP).
    - Cannot route packets through the IP network.



Industrial Ethernet

Introduction

- 3 classes:
  - **Class 3**: Modified Ethernet + custom apps
    - Support hard real-time requirements (latency ≥ 1 ms).
    - Some protocol modifications are required to support real-time (e.g., IEEE 1588 PTP).
    - Protocol modifications to the original Ethernet implementations
    - Requires some custom Ethernet equipment
    - Cannot route packets through the IP network.



Industrial Ethernet

Applications

- **Manufacturing and logistics**
  - When capturing data in the industrial environment, the Industrial Ethernet carries out the management of the data to the IT network in real-time for the tracking control.
- **Outdoor applications**
  - When using motion sensors it is common to use the network to deliver Power over Ethernet (PoE), as this simplifies wiring and makes it easier to control the device.
- **Electricity substations**
  - Network devices are vulnerable to electrical networks by levels of electromagnetic interference. Cables used in Industrial Ethernet can simplify installation.
- **Vehicles and trains**

Industrial Ethernet

Main technologies

- The most widely adopted Industrial Ethernet technologies.

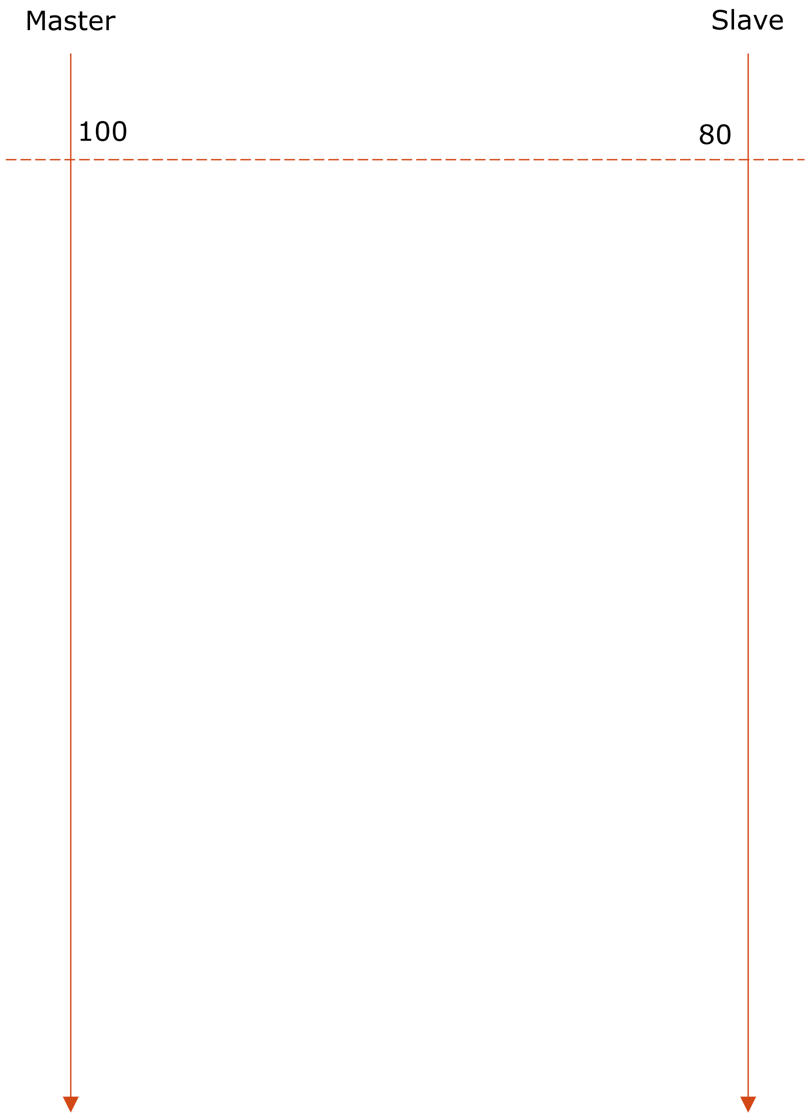
Technology	Technical approach	Class	Standard
Profinet-IO	Ethernet with priorities and VLANs Modified Ethernet with deterministic scheduling (IRT)	2/3	IEC 61158 IEC 61784 Communication Profile 10
EtherNet/IP	TCP/IP over Ethernet	1	IEC 61158 IEC 61784 Communication Profile 2
EtherCAT	Modified Ethernet with master-slave ring topology and summation frame	3	IEC 61158 IEC 61784 Communication Profile 12
Modbus TCP	TCP/IP over Ethernet	1	IEC 61158 IEC 61784 Communication Profile 15
Powerlink	Ethernet with priorities and VLANs	2	IEC 61158 IEC 61784 Communication Profile 13

IEEE 1588 over Ethernet

- The lack of real-time capabilities of early Ethernet was the primary barrier for the adoption of this technology in the industrial field.
- Main problem: lack of a common timing reference among the sub-systems, which allows to precisely guarantee synchronization (very important for some apps).
  - GPS is not a good solution, because it does not work indoors, and may be inaccurate.
- Solution: Use communication network to distribute timing signals, which allow clocks (at the transmitter and receiver) to become synchronized.
  - Via the **IEEE 1588 Precision Time Protocol (PTP)**.

IEEE 1588 over Ethernet (example)

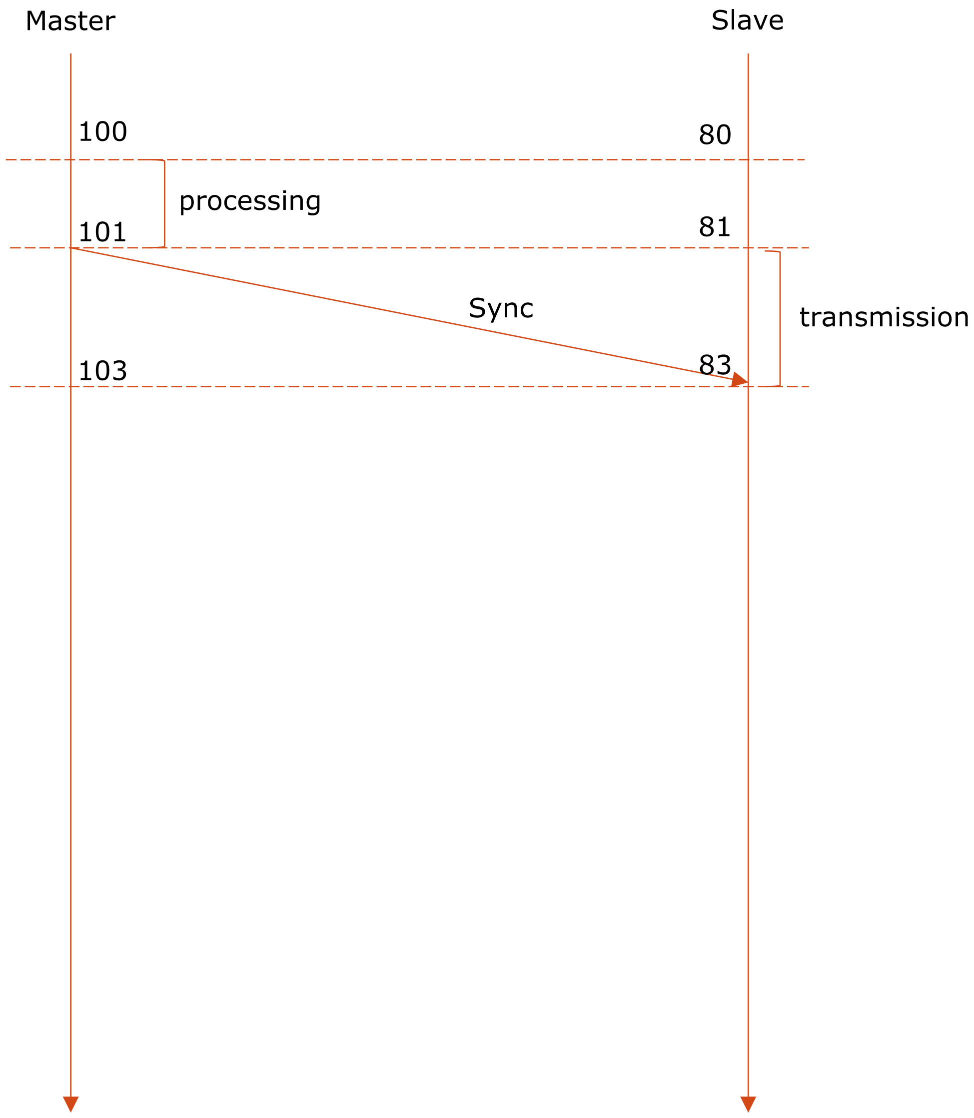
1. Assume that the clock of the Master and the clock of the Slave are not synchronized (at the beginning).
   - Assume that the time offset is -20 s.
2. PTP starts at 100 s for M (=80 s for S).



Industrial Ethernet

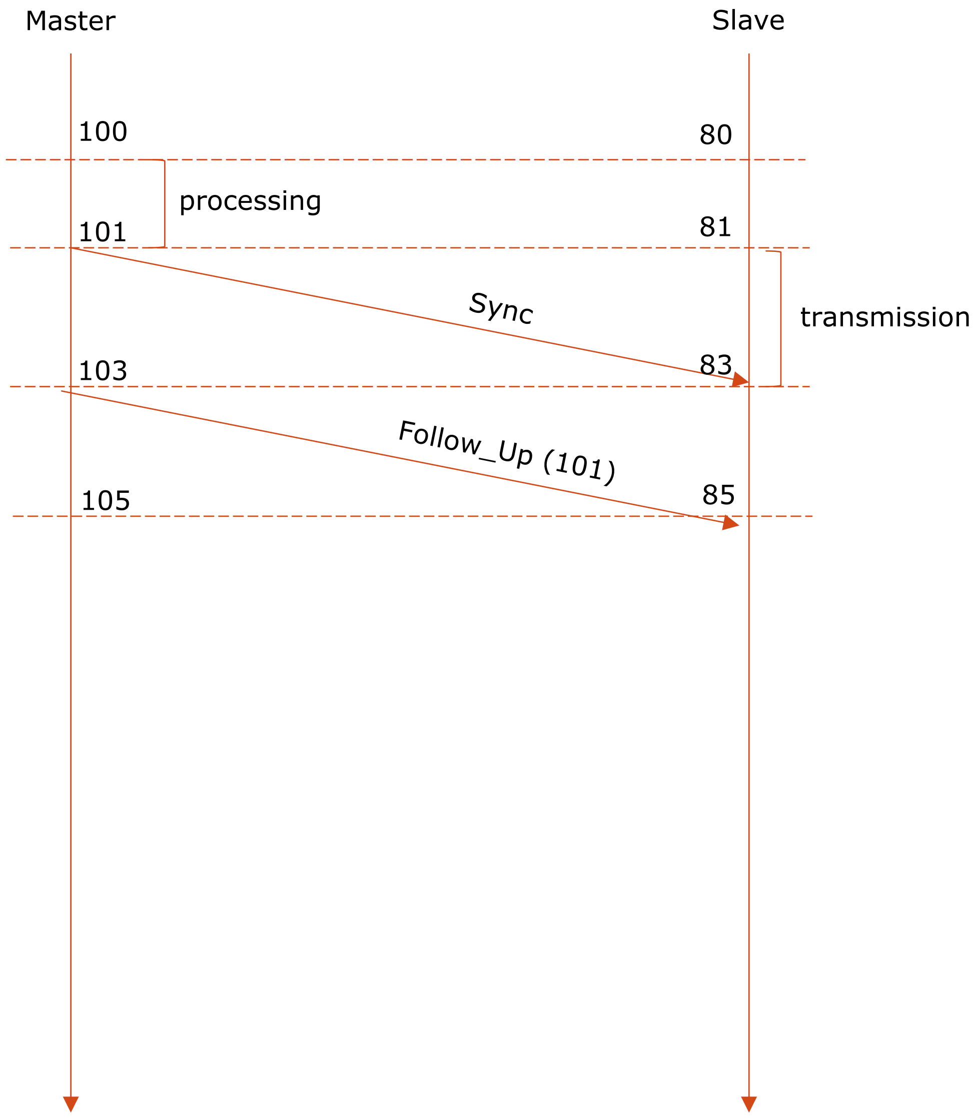
IEEE 1588 over Ethernet (example)

3. M sends a **Sync** message to S.
   - Processing time of 1 s
   - Transmission/network time of 2 s.
   - The message is received at S at time 83 (= 103 for M).



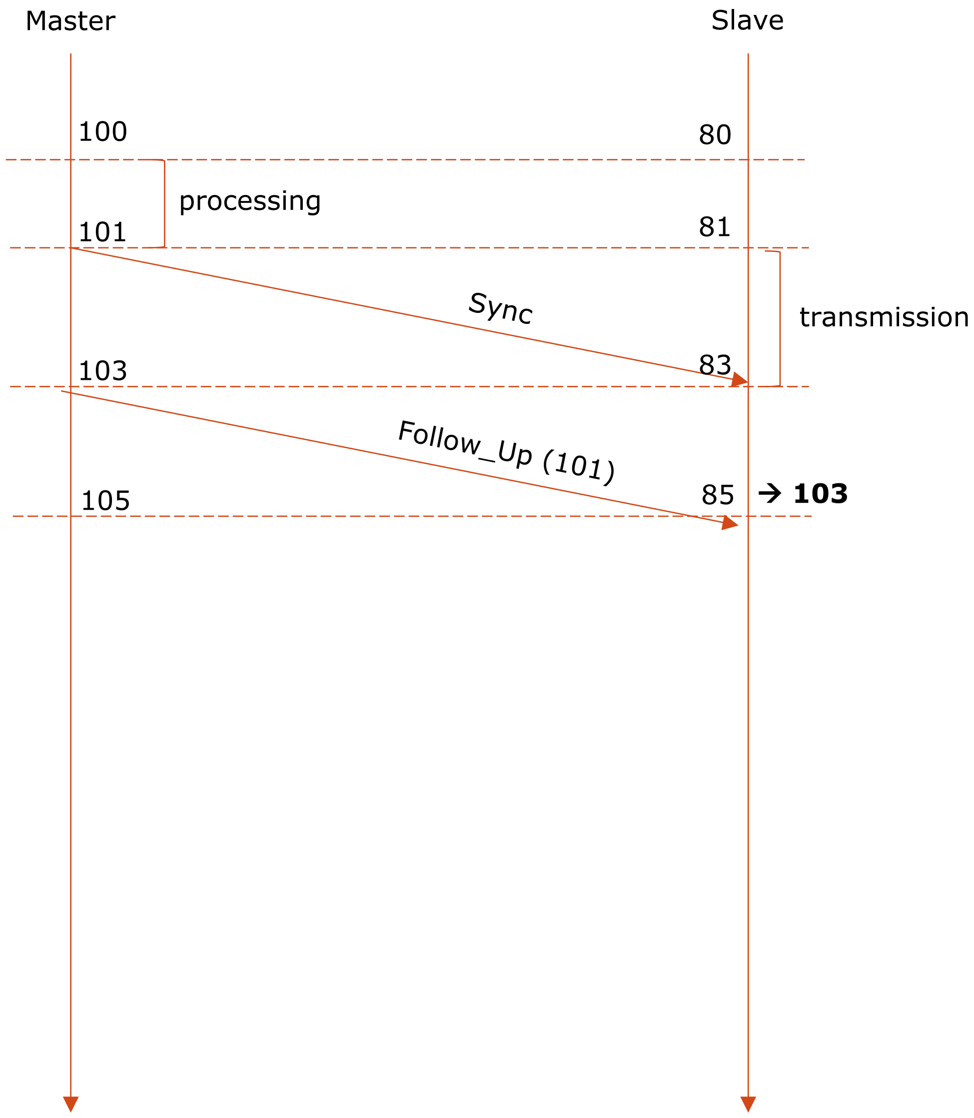
IEEE 1588 over Ethernet (example)

4. At 103 s, M sends a **Follow_Up** message to S, which contains the value of the Master’s clock when the Sync message was generated, after the processing (=101).



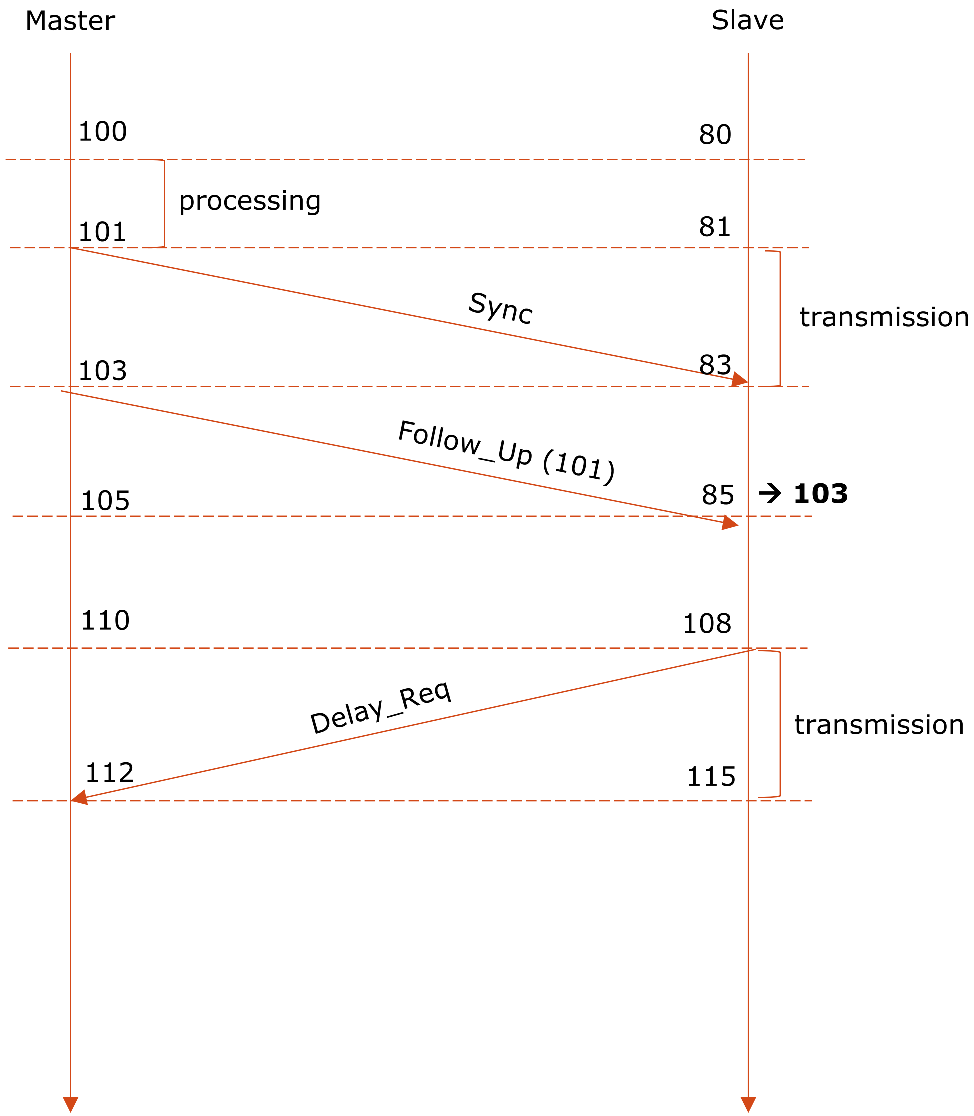
IEEE 1588 over Ethernet (example)

5. S compares the value of the Follow_Up (101) with the value of its clock when the Sync was received (83).
6. S subtracts the two values: 101-83=18.
7. S changes adjusts its current clock (85) with the new offset (18).
   - The new clock becomes 85+18=103.
   - The Slave's new clock (103) is still not synchronized with the Master's clock (105).
   - The difference is due to the transmission time.



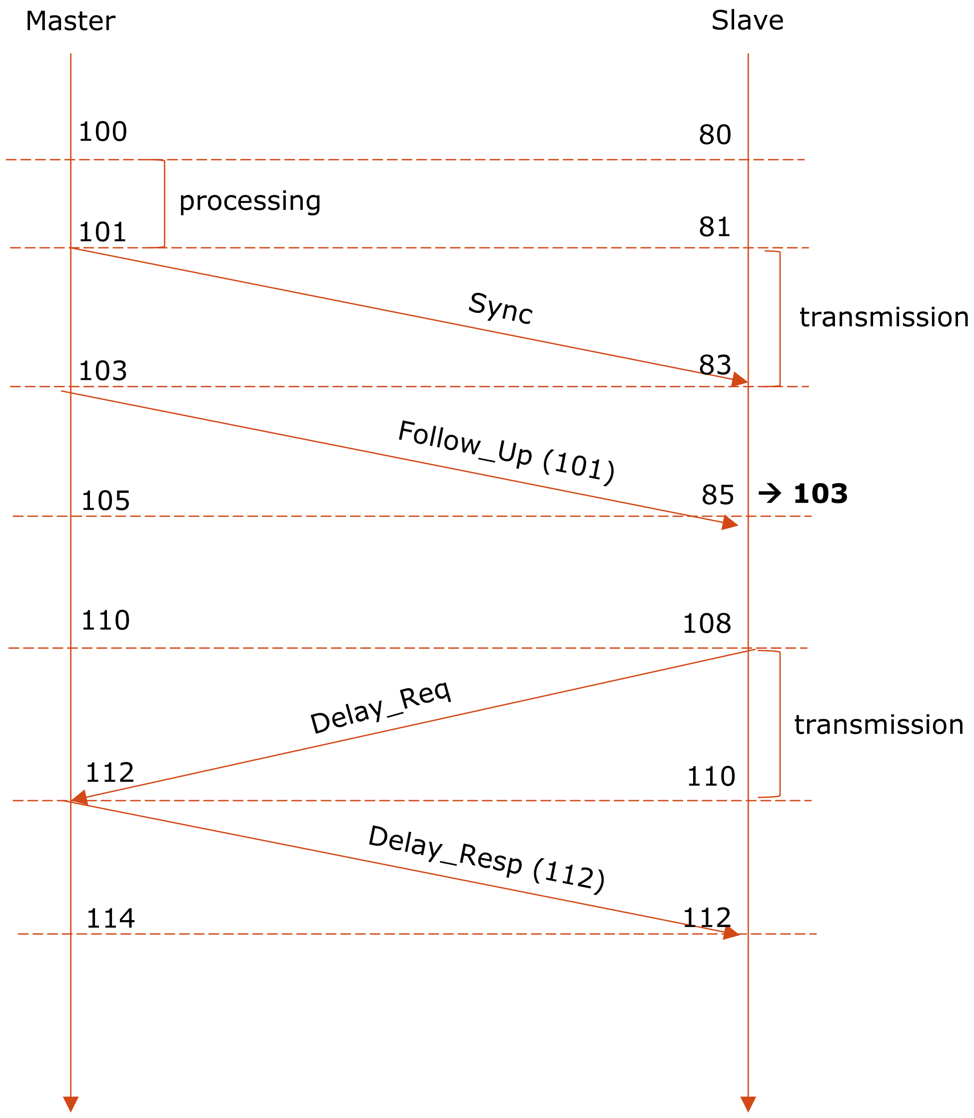
IEEE 1588 over Ethernet (example)

8. S sends a **Delay_Req** at time 108 s (=110 at M as they are not yet fully sync'ed).
9. M receives the message at time 112 s, due to the transmission and network delays.



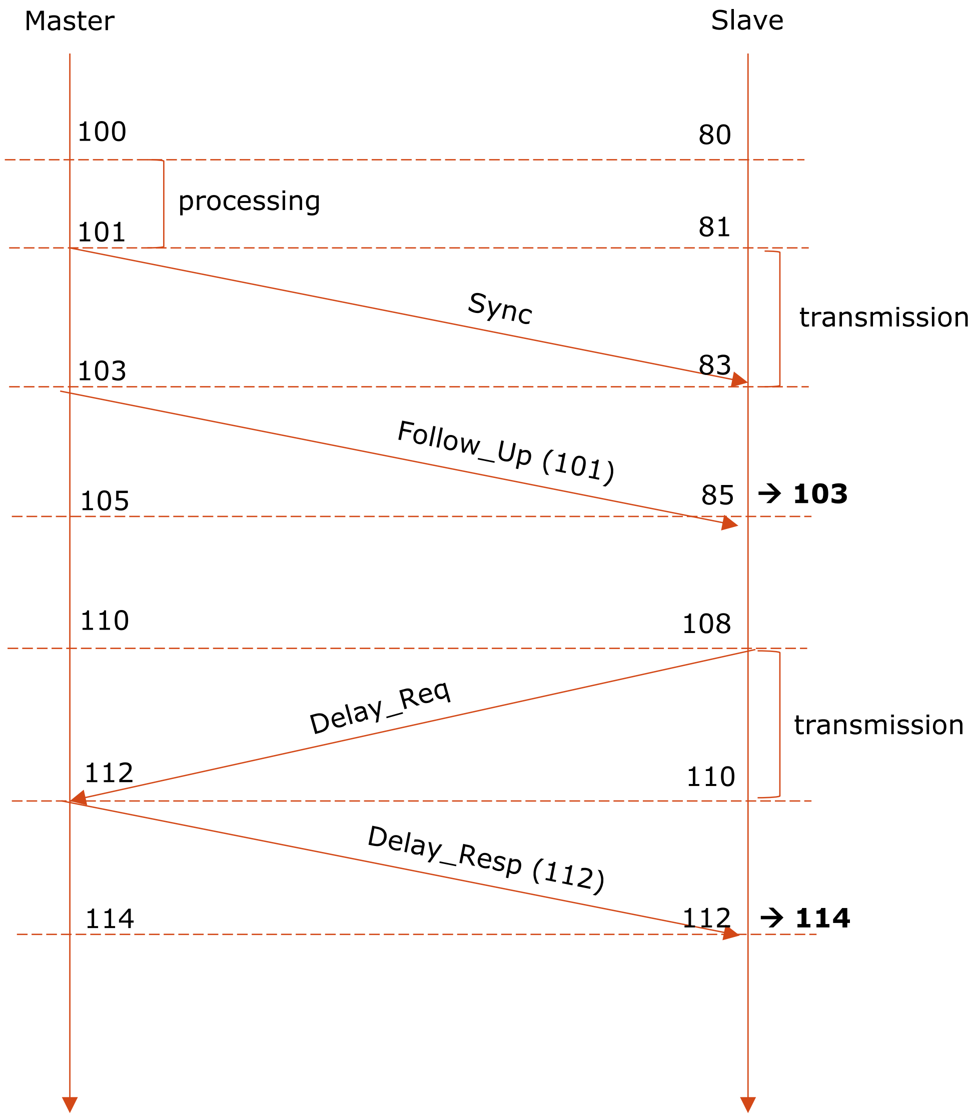
IEEE 1588 over Ethernet (example)

10. M sends a **Delay_Resp** message to S, which contains the value of the Master's clock when the Delay_Req message was received (=112).



IEEE 1588 over Ethernet (example)

11. S compares the value of the Delay_Resp (112) with the value of its clock when the Delay_Req was generated (108).
12. S subtracts the two values: 112-108=4.
13. S changes adjusts its current clock (112) with the new offset divided by 2 (4/2=2), since it is due to 2 message trasnmissions (Delay_Req + Delay_Resp).
    - The new clock becomes 112+2=114.
    - The Slave’s new clock is **fully synchronized**.



Single Pair Ethernet

- Another problem: Ethernet is not compatible with the constraints of the industrial scenario, including **power consumption** and the **limited space** for the wires.
- New version of Ethernet for industry: **Single Pair Ethernet (SPE)**.
    - Compared to ordinary Ethernet, which tipically uses four twisted pairs of wires (eight wires in total), SPE uses a **single twisted pair** of wires (two wires in total), so it can connect smaller and simpler sensors.
    - **(Looser) data rate**: from 10 Mbps to 1 Gbps (vs. up to 100 Gbps).
    - **(Higher) range**: up to 1 km (vs. up to 100 m).
    - **(Lower) cost**: Generally cheaper for applications that do not require high bandwidth, with reduced cabling complexity and lower material costs.

Industrial Ethernet

Applications

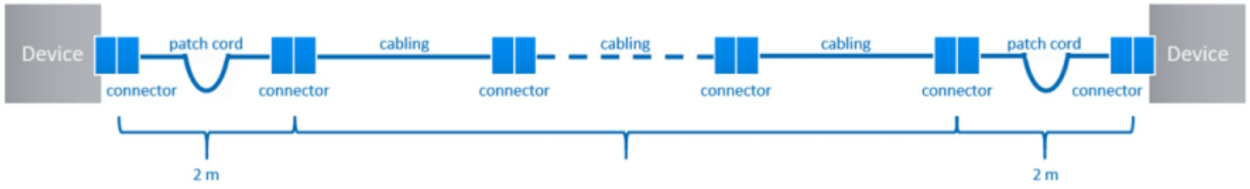
- **E-transportation**
  - Visual and acoustical passenger information systems (PIS); Seat reservation; CCTV; Passenger counting visual (APC); Infotainment.
  - SPE offers weight reduction up to 55%: 3 kg/100 m vs. 4,6 kg/100 m with standard Eth.
  - For battery-operated vehicles, weight directly translates into better battery efficiency.
- **Automation**
  - Perinet GmbH injection molding case study
- **Monitoring and reporting**
  - Example: smart monitoring of low shelf life goods. An SPE system can use sensors embedded within the bread case itself that monitor fill level of the product on the shelves.

Industrial Ethernet

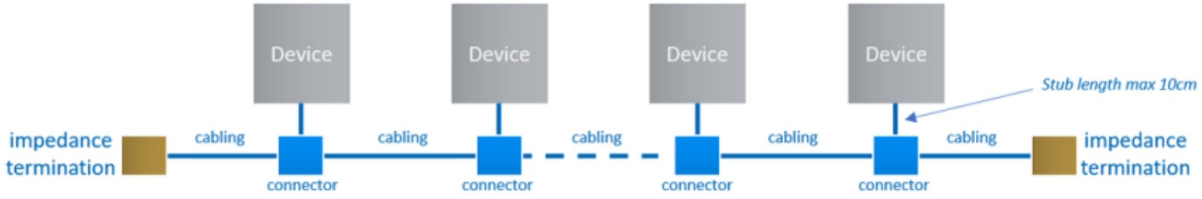
Single Pair Ethernet

- 10BASE-T1S (IEEE 802.3cg)

Data rate	Duplexing	Range
10 Mbit/s	Half-duplex	15 m (point-to-point) 25 m (multidrop topology)



POINT-TO-POINT



MULTIDROP
No switches, less cable, reduced power.

Industrial Ethernet

Single Pair Ethernet

- 10BASE-T1S (IEEE 802.3cg)
- **Physical Layer Collision Avoidance (PLCA) scheme**
  - Prevents collision in a multidrop topology.
  - A Master periodically sends beacon frames that start an ordered cycle of transmissions.
  - When it’s its turn, a device can transmit or “pass the turn” to the next device.
  - Similar to a ring token-passing topology.
- Use cases: applications connecting sensors and actuators, e.g., in cars targeting compact implementations.

Industrial Ethernet

Single Pair Ethernet

- 10BASE-T1L (IEEE 802.3gc)

Data rate	Spectrum	Range
10 Mbit/s	20 MHz	1000 m (point-to-point)

- Use cases: industries where remote sensing and control is required, e.g., building automation, elevators, factory automation, energy supply and monitoring, automation of waterworks, wastewater treatement.

Industrial Ethernet

Single Pair Ethernet

- 100BASE-T1 (IEEE 802.3bw)

Data rate	Spectrum	Range
100 Mbit/s	166 MHz	15-40 m (point-to-point)

- Use cases: automotive industry towards autonomous driving for cooperative perception, where transmissions of large amounts of sensory data (e.g., from LiDAR and camera sensors) are required.

Single Pair Ethernet

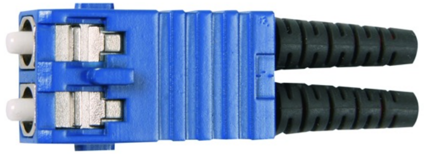
- 2.5/5/10GBASE-T1 (IEEE 802.3ch)

Data rate	Spectrum	Range
Up to 10 Gbit/s	4-5 GHz	15 m (point-to-point)

- Use cases: Advanced Driver Assistance Systems (ADAS), high-performance computing in vehicles, high-definition sensor fusion, real-time control of robotic systems with high-speed data transfer between industrial machines.

Industrial Ethernet

Industrial connectors



- "Normal" Ethernet **plastic** connectors, like the RJ-45 or the SC-RJ (for fiber optic cabling), may not be suitable in the industrial environment due to potentially critical situations of distress (e.g., temperature, pressure, radiation, etc.) that connectors may be subject to.
- Connectors may be chosen based on the environment in which they are deployed:
  - **M**echanical stress
  - **I**ngress (water, dust, etc.)
  - **C**limatic and chemicals (temperature, humidity, UV radiation, etc.)
  - **E**lectromagnetic

MICE

- Example for industrial scenario: **IP64 connector.**

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10 – IoT technologies (wired)
EtherCAT

Marco Giordani (marco.giordani@unipd.it)
Department of Information Engineering (DEI) – SIGNET Research Group
University of Padova – Via Gradenigo 6/B, 35131, Padova (Italy)

EtherCAT

Overview

- **Class 3** Industrial Ethernet standard.
  - Modified Ethernet.
  - Custom hardware/equipment to support ultra-fast “on the fly” processing up to 1 Gbit/s.
  - **Hard real-time** applications (latency of a few ms), e.g., robotics, human prothesis.
- High-precision time synchornization among the Slaves with a **Distributed Clock** mechanism (a variant of IEEE 1588).
- EtherCAT requires a custom hardware/equipment to support ultra-fast “on the fly” processing within the **daisy chain ring**.

EtherCAT real-time protocols
EtherCAT standard and equipment
PHY Layer

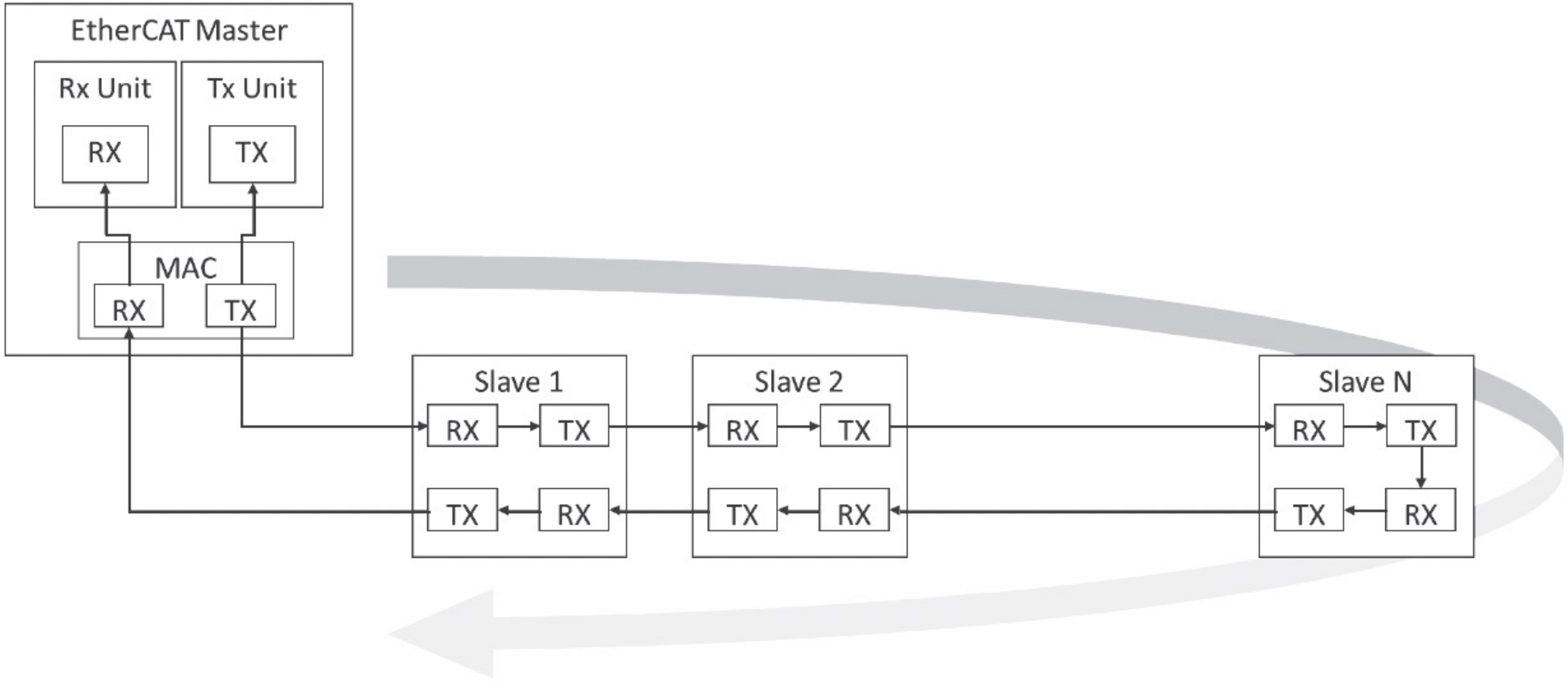
EtherCAT

Architecture

- **Master-slave daisy chain ring** (aka bidirectional line).
  - Deterministic communication (cycle time ≤100 μs).
  - The Master sends frames that pass along the slaves.
  - Slaves read and process the information in the frame «on the fly», inserting responses if requested (summation-frame).

EtherCAT

Architecture



Frame structure

EtherCAT telegram						
	Ethernet header			EtherCAT frame		Ethernet
Preamble	DA	SA	Type	Frame header	Data	FCS
8 bytes	6 bytes	6 bytes	2 bytes	2 bytes	0…1498 bytes	4 bytes

Length	Res.	Type
11 bits	1 bit	4 bits

- **Length**: Cumulative length of the EtherCAT datagrams.
- **Res**: Reserved for future use.
- **Type**: Protocol type.

EtherCAT

Frame structure

EtherCAT telegram

Ethernet header | EtherCAT frame | Ethernet

Preamble	DA	SA	Type	Frame header	Data	FCS
8 bytes	6 bytes	6 bytes	2 bytes	2 bytes	0…1498 bytes	4 bytes

1-st EtherCAT datagram	…	1-th EtherCAT datagram

Datagram header	Data	Working counter (trailer)
10 bytes	0…1486 bytes	2 bytes

Cmd	IDX	Address	Len	R	C	M	IRQ
8 bits	8 bits	32 bits	11 bits	3 bits	1 bit	1 bit	16 bits

EtherCAT

Frame structure

1-st EtherCAT datagram	…	1-th EtherCAT datagram

Datagram header	Data	Working counter (trailer)
10 bytes	0…1486 bytes	2 bytes

Cmd	IDX	Address	Len	R	C	M	IRQ
8 bits	8 bits	32 bits	11 bits	3 bits	1 bit	1 bit	16 bits

- **Cmd**: EtherCAT command type.
- **IDX**: The ID used by the Master for the identification of duplicates/lost datagrams.
- **Address**: Auto-increment (configured logical address).
- **Len**: Length of the data within the same datagram.
- **R**: Reserved.
- **C**: Flag to avoid a frame to circulate forever.
  - 0: Frame does not circulate; 1: Frame has circulated once.
- **M**: Flag to indicate that there are more EtherCAT datagrams in the same frame.
- **IRQ**: EtherCAT Event Request register of all slave devices combined with a logical OR.
- **Working Counter**: Incremented if an EtherCAT device was successfully addressed and a read/write operation was executed successfully.
  - The Master can check whether a datagram was processed successfully by comparing the value to be expected for the Working Counter with the actual value of the Working Counter.

Frame structure: Cmd

More details:
https://infosys.beckhoff.com/english.php?content=../content/1033/tc3_io_intro/1257993099.html

Cmd	Abbreviation	Name	Description
0	NOP	No Operation	A slave ignores the command.
1	APRD	Auto Increment Read	A slave increments the address. A slave writes the data it has read to the EtherCAT datagram if the address received is zero.
2	APWR	Auto Increment Write	A slave increments the address. A slave writes data to a memory area if the address received is zero.
3	APRW	Auto Increment Read Write	A slave increments the address. A slave writes the data it has read to the EtherCAT datagram and writes the newly acquired data to the same memory area if the received address is zero.
4	FPRD	Configured Address Read	A slave writes the data it has read to the EtherCAT datagram if its slave address matches one of the addresses configured in the datagram.
5	FPWR	Configured Address Write	A slave writes data to a memory area if its slave address matches one of the addresses configured in the datagram.
6	FPRW	Configured Address Read Write	A slave writes the data it has read to the EtherCAT datagram and writes the newly acquired data to the same memory area if its slave address matches one of the addresses configured in the datagram.
7	BRD	Broadcast Read	All slaves write a logical OR of the data from the memory area and the data from the EtherCAT datagram to the EtherCAT datagram. All slaves increment the Position field.
8	BWR	Broadcast Write	All slaves write data to a memory area. All slaves increment the Position field.
9	BRW	Broadcast Read Write	All slaves write a logical OR of the data from the memory area and the data from the EtherCAT datagram to the EtherCAT datagram; all slaves write data to the memory area. BRW is typically not used. All slaves increment the Position field.
10	LRD	Logical Memory Read	A slave writes data it has read to the EtherCAT datagram if the address received matches one of the FMMU areas configured for reading.
11	LWR	Logical Memory Write	Slaves write data to their memory area if the address received matches one of the FMMU areas configured for writing.
12	LRW	Logical Memory Read Write	A slave writes data it has read to the EtherCAT datagram if the address received matches one of the FMMU areas configured for reading. Slaves write data to their memory area if the address received matches one of the FMMU areas configured for writing.
13	ARMW	Auto Increment Read Multiple Write	A slave increments the Address field. A slave writes data it has read to the EtherCAT datagram when the address received is zero, otherwise it writes data to the memory area.